2004

Provenance of tertiary conglomerates, eastern San Francisco Bay Area, California

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PROVENANCE OF TERTIARY CONGLOMERATES, EASTERN SAN FRANCISCO BAY AREA, CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

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May 2004

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ABSTRACT

PROVENANCE OF TERTIARY CONGLOMERATES, EASTERN SAN FRANCISCO BAY AREA, CALIFORNIA

by James P. Walker

This thesis presents the results of 16 point counts of conglomerates in the Tertiary Kirker Formation and the Miocene San Pablo Group (the Cierbo, Briones and Neroly sandstones). The Kirker Formation contains andesitic clasts, pointing to a Miocene age of less than 20 Ma. The Kirker and Cierbo have a metamorphic-dominated provenance, whereas the Neroly is dominated by Sierran volcanic clasts. Basalt clasts, derived from the northern Sierra, are absent from the Neroly south of Mount Diablo. This absence, debris-flow deposits in the Neroly, and angular unconformities between the units north of Mount Diablo suggest that a paleohigh occupied the present position of Mount Diablo. To the west at Happy Valley, the Neroly contains no volcanic clasts, suggesting a previously greater separation between it and the Berkeley Hills Volcanics due to later dextral slip.

ACKNOWLEDGEMENTS

This study has benefited from the help of many people. Chief among them are David Andersen, Andrei Sarna-Wojcicki, Raymond Sullivan, Richard Sedlock, Thomas Bullen, Russell Graymer, Jeffery Unruh, and Anna Sojourner. I owe a special thanks to Anna Buising under whom this work was begun.

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INTRODUCTION

The purpose of this thesis is to provide a detailed survey of the coarse-clastic deposits of the Oligocene (?) Kirker Formation and middle to upper Miocene San Pablo Group, composed of the Briones, Cierbo, and Neroly sandstones, in the eastern San Francisco Bay area, California (Fig. 1). This study will help refine our knowledge of sediment provenance and dispersal in order to construct the history and geometry of the depositional basin. These advances contribute to a better understanding of the underlying mechanisms for the evolution of the basin during late Tertiary time.

The depositional basin for the San Pablo Group may have formed in response to the onset of strike-slip when the California continental margin changed from a subduction zone to the present transform margin with the development of the San Andreas system (Buising and Walker, 1995). A second possibility is that the basin formed during the older subduction regime and was modified by later transform tectonics. The geometry and sedimentation patterns of the basin, and other geological features (folds, faults, uplifted regions, and volcanism) associated with it, can give us some clues as to whether it formed in a subduction-dominated or strike-slip-dominated environment and in what kind of an environment it matured. By increasing our understanding of the timing of basin development, we will be better able to answer the questions of how and under what conditions the basin formed.

Volcanic clasts in the conglomerate beds can help constrain the correlations of the formations and the timing of basin development. By using the coarse-clast composition to reflect provenance, we can also test issues in stratigraphic nomenclature for units within the San Pablo Group and for the Kirker Formation. The testing of unit nomenclature is necessary because all of the units were originally

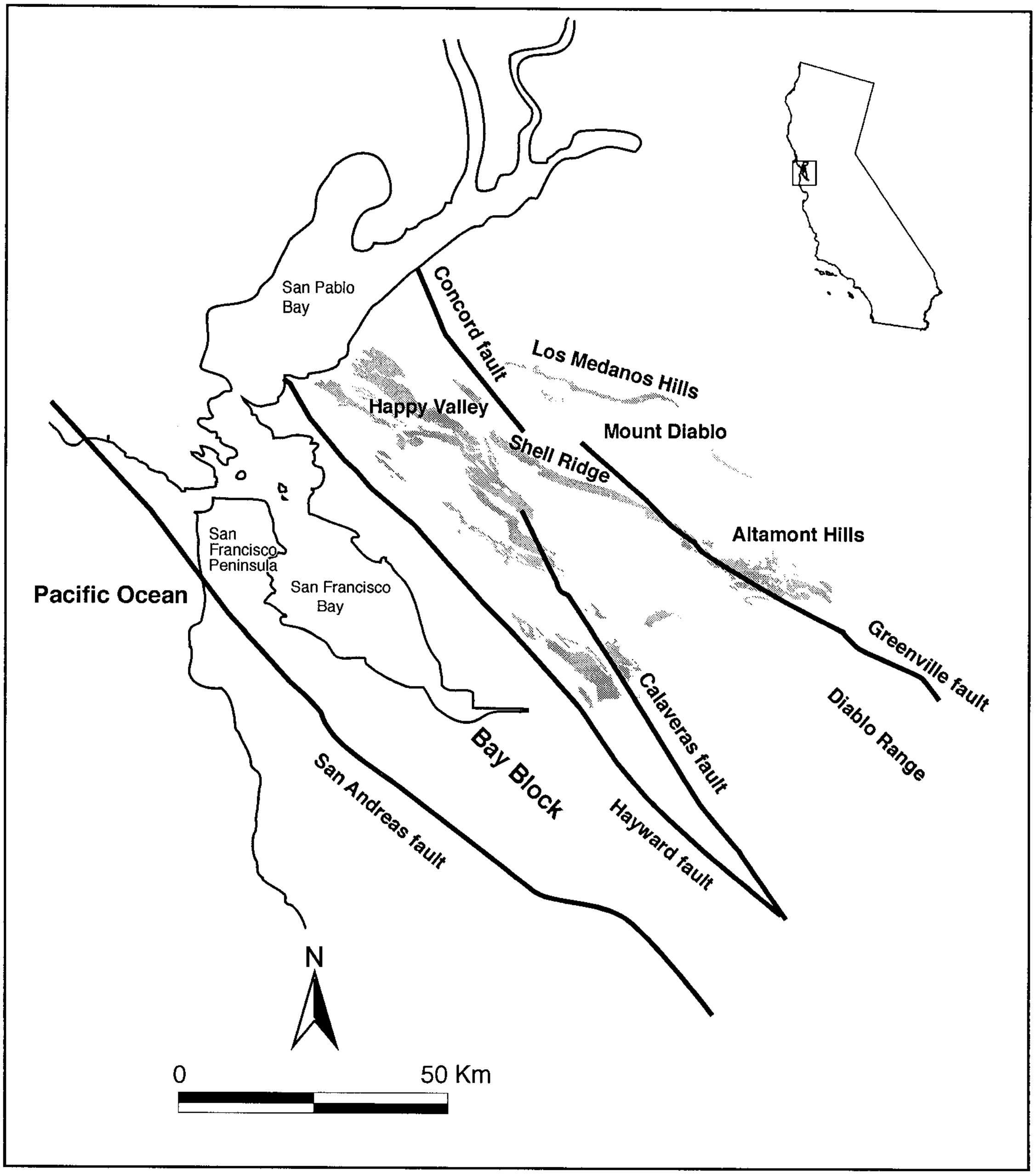

Figure 1. Map of the greater San Francisco Bay area, California, showing major faults and the outcrop pattern, in gray, of the Kirker Formation and the San Pablo Group, which define the Neogene depositional basin studied here (after Graymer et al., 1994).

defined as biostratigraphic units and not as lithostratigraphic units (Lawson, 1914; Clark, 1915).

In order to address the issues described above, 16 coarse-clast counts were done in the Kirker Formation and the San Pablo Group. Clast sizes included in the study are pebbles and cobbles (4-256 mm). Clasts this size require greater energy for transport than sand and are, therefore, more accurate indicators of a basin's geometry than sand (Sadler et al., 1989). Gravel-size clasts may also allow the recognition of previously unidentified sub-basins and other transport barriers within the basins.

GEOLOGIC SETTING

Neogene sedimentary rocks in the east Bay area (Fig. 1) may record the onset and development of strike-slip motion in the region. Prior to 24 Ma an oceanic plate was being subducted beneath the western edge of California, driving Tertiary arc volcanism in the Sierra Nevada (Fig. 2) and creating an outer arc bulge where the Coast Ranges are now located. The San Andreas fault transform system began to develop at approximately 24 Ma after the East Pacific Rise came into contact with the North American Plate. As the plate motion changed from subduction to right lateral strike slip, the Mendocino and Rivera triple junctions formed at the northern and southern ends, respectively, of the evolving San Andreas fault system (Atwater, 1970). When the ridge made contact with the continent (or slightly before), the production of seafloor stopped. As the transform system developed, a slab gap formed between the two triple junctions (Severinghaus and Atwater, 1990). The northern terminus of the San Andreas fault (the Mendocino Triple Junction) migrated northward, reaching the vicinity of the Bay area at approximately 15 Ma (Fox et al., 1985). Between the North American and Pacific plates several structural blocks were created that were partially or completely decoupled from the underlying lithosphere. In the Bay area (Fig. 1) these blocks are bounded by the San Andreas, Hayward, Calaveras, and related faults (Page, 1982).

In the western portions of the Bay area, Miocene biogenic chert and phosphatic units of the Monterey Group represent deposition in sediment-starved, deep-water basins between 20 and 15 Ma. East of the Calaveras fault, rocks of this age represent shallow-water marine facies. During at least part of this time, clastic material derived from Franciscan rocks in the Coast Ranges appears to have been shed into the basins from the northeast (Hill, 1979).

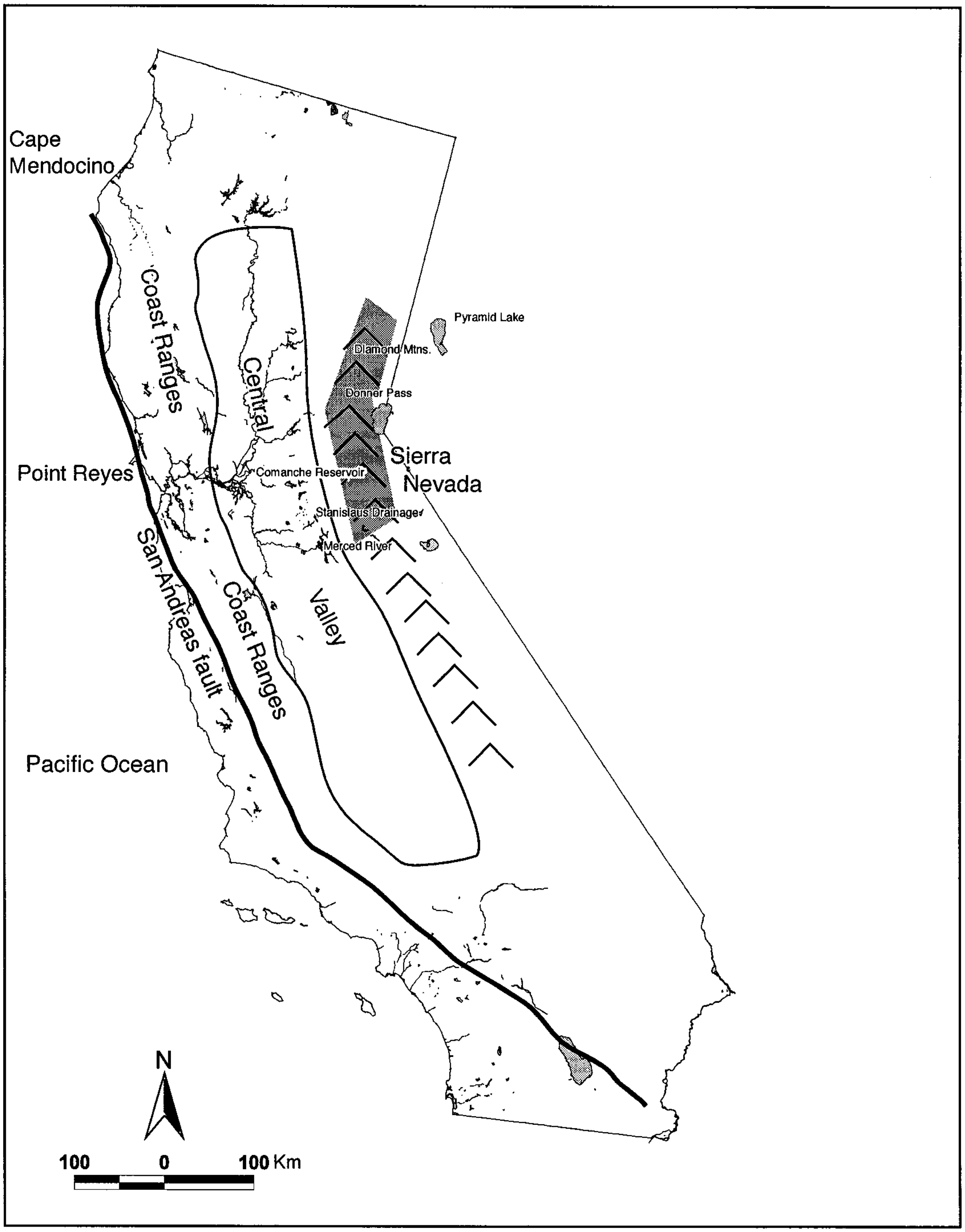

Figure 2. Map of California showing major physiographic features. Tertiary Sierran volcanics are shown in dark gray, geology after Jennings et al., 1977.

On the San Francisco Peninsula, the eruption of the Page Mill Basalt (Fig. 3) at 15 Ma marks the beginning of rupture on the San Andreas fault (Fox et al., 1985) or, alternatively, the segmentation of the peninsular block due to borderland deformation (A. V. Buising, personal commun., 1995).

The Bay area was thus an open coastal region until about 15 Ma. The shoreline was located approximately at the present-day location of Mount Diablo, and sediment-starved, deep-water basins and their associated sills lay to the west (Buising and Walker, 1995). To the north, the outer-arc bulge was already high enough to act as a source terrain (Hill, 1979). To the south, the outer-arc bulge probably formed a topographic high similar to that in the north (Harms et al., 1992).

By 10 Ma, the Berkeley Hills volcanic center (Fig. 3) was active (Grimsich et al., 1996), as was the Hayward fault. The Bay Block (Fig. 1), which previously had been a deep-water basin (between the future San Andreas and Hayward faults), became a topographic high by 10 Ma, shedding detritus to the east. These sediments formed the Contra Costa Group and related units. They were deposited on a subaerial plain that sloped to the east, and some of the shallow-marine deposits of the San Pablo Group have been inferred to represent their marine equivalents to the east (Graham et al., 1984).

North of San Pablo Bay, several small outcrops of the San Pablo Group represent the northern margin of the depositional basin for the San Pablo Group, called the San Pablo embayment. To the south was the nascent Diablo Range, which at least locally was the dominant source of sediment for the southern portions of the San Pablo Group (Chetelat, 1995). Between Mount Diablo and the Diablo Range, the uppermost fluvial units of the San Pablo Group (the Neroly Sandstone)

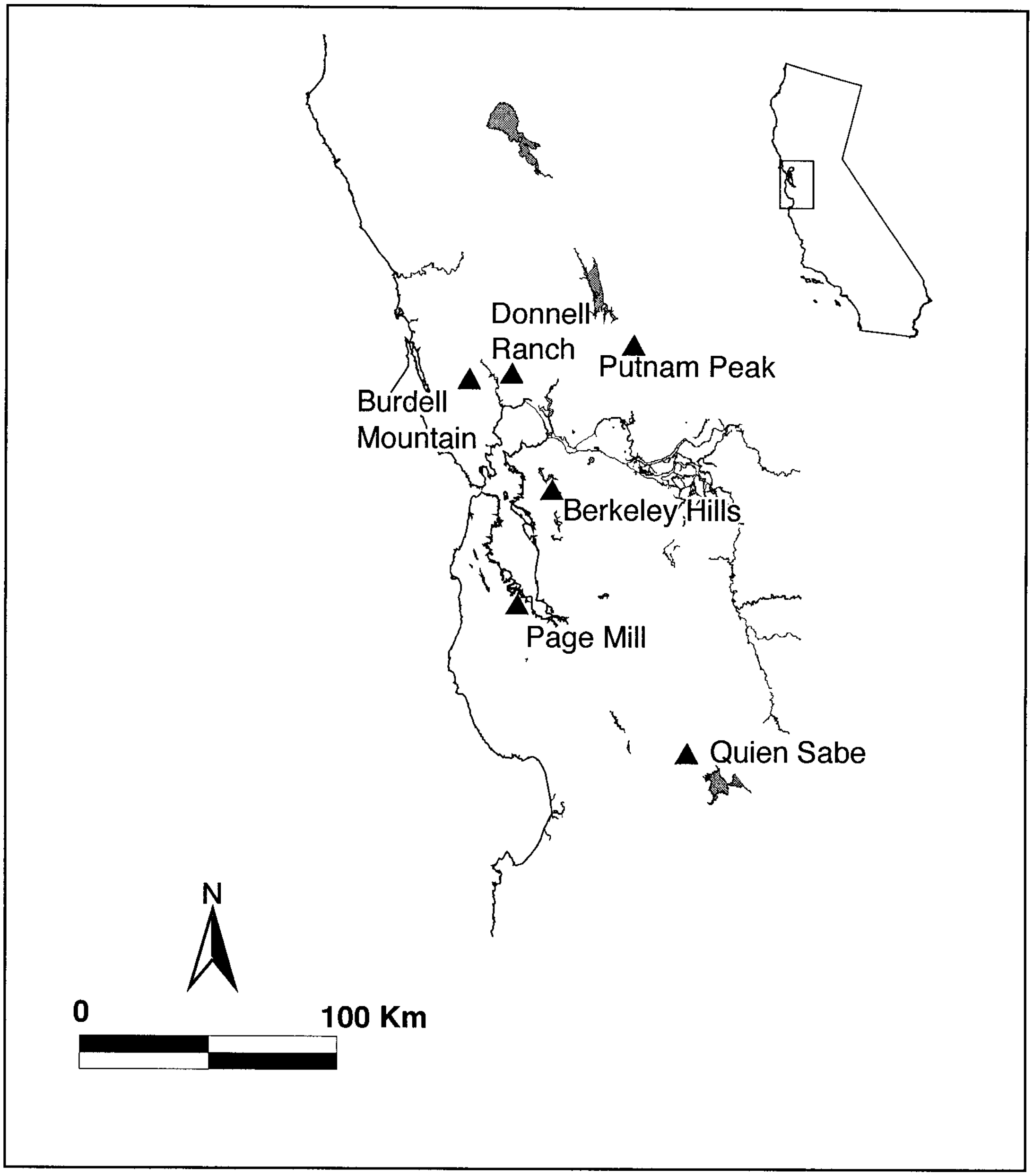

Figure 3. Locations of Coast Range volcanic centers (after Fox et al., 1985, and Graymer et al., 2002).

are coeval with the base of Carbona fanglomerates, which mark the beginning of uplift in the region (Buising and Walker, 1995).

The paleogeography of the Bay area at about 10 Ma was dominated by a bay, represented by the San Pablo Group, that was similar to but larger and centered farther to the east than modern San Francisco Bay (Buising and Walker, 1995). The bay opened to the Pacific Ocean at its southern end in its early history (Briones), and later (Neroly) it was open to the north (Buising and Walker, 1995; Chetelat, 1995). It is also possible that during some or all of this history the bay was open at both ends. If so, the Bay Block (Fig. 1) of Graham et al. (1984) would have been an island. In this case the marine portions of the San Pablo Group represent a strait between the mainland and this island.

PREVIOUS WORK

Two areas outside the thesis area that are important to this study are the Sierra Nevada, where rocks represent Tertiary arc volcanism, and the Coast Ranges (Fig. 2). A clear understanding of Sierran lithologies, stratigraphy, and chronology is necessary in order to understand the implications of many of the eastern-sourced gravel-size clasts encountered in this study. Likewise, an understanding of the Coast Range lithologies is also important because these rocks are local sources of clasts and provide important information on local tectonics.

Within the study area, the original mapping of the Tertiary units in the East Bay area was done before standardization of unit nomenclature under the North American Stratigraphic Code. The units were originally defined using biostratigraphic (macrofaunal assemblage) criteria (Lawson, 1914; Clark, 1915). Subsequent mappers in the area used the existing unit names but attempted to reapply them as lithostratigraphic units (e.g., Trask, 1922; Hill, 1979; Graymer et al., 1994). This proved to be difficult because the stratigraphic nomenclature cannot be uniformly applied throughout the study area.

Sierran Formations

Turner (1894, 1898), Ransome (1898), and Lindgren (1912) did the first mapping in the Sierra Nevada and provided the basis for much of the work that followed. Their work showed the basic geologic relationships of the Mesozoic granitic basement; the older metamorphic roof pendants, composed primarily of metasedimentary and metavolcanic rocks; and younger sedimentary units, such as the auriferous gravels. All of these rocks underlie the Tertiary volcanic sequence. In addition, their early mapping showed the internal stratigraphic relationships within the Tertiary volcanics.

The stratigraphic nomenclature followed here for Tertiary volcanic rocks in the Sierra Nevada (Fig. 4) was taken largely from Durrell (1959) and Slemmons (1966); the revised stratigraphy of Wagner et al. (2000) was used for the northern Sierra. Neither Durell nor Slemmons organized the volcanic units they studied into a regional stratigraphic framework. Dalrymple (1963, 1964) conducted a geochronologic reconnaissance of Tertiary volcanic formations using potassium-argon dating techniques.

According to the geochronology constructed from the data collected by Dalrymple (1963, 1964), Durrell (1987), Wagner and Saucedo (1990), Saucedo et al. (1992), and Page et al. (1995), Tertiary volcanism in the Sierra Nevada lasted from approximately 35 Ma to 1 Ma (Fig. 5, Table 1). Sierran Tertiary volcanism may be divided into three distinct phases, based on composition and age (Fig. 4).

The oldest volcanic rocks are rhyolitic, and are represented in the northern Sierra by the Delleker Formation and to the south by the Valley Springs Formation and the laterally equivalent Hartford Hills Rhyolite. K/Ar and Ar/Ar dates show that the main period of rhyolitic volcanism was from 35 Ma to 20 Ma (Fig. 5).

The Delleker and Valley Springs formations were deposited as ash flows and locally contain significant amounts of quartzite pebbles and cobbles similar to those found in the underlying auriferous gravel (Durrell, 1959). In the southern outcrops of the Delleker, metavolcanic and granitic gravel is also present. Durrell (1959) suggested that the metavolcanic and granitic clasts have a probable source northeast of Pyramid Lake (Fig. 2). The Valley Springs Formation is characterized in hand

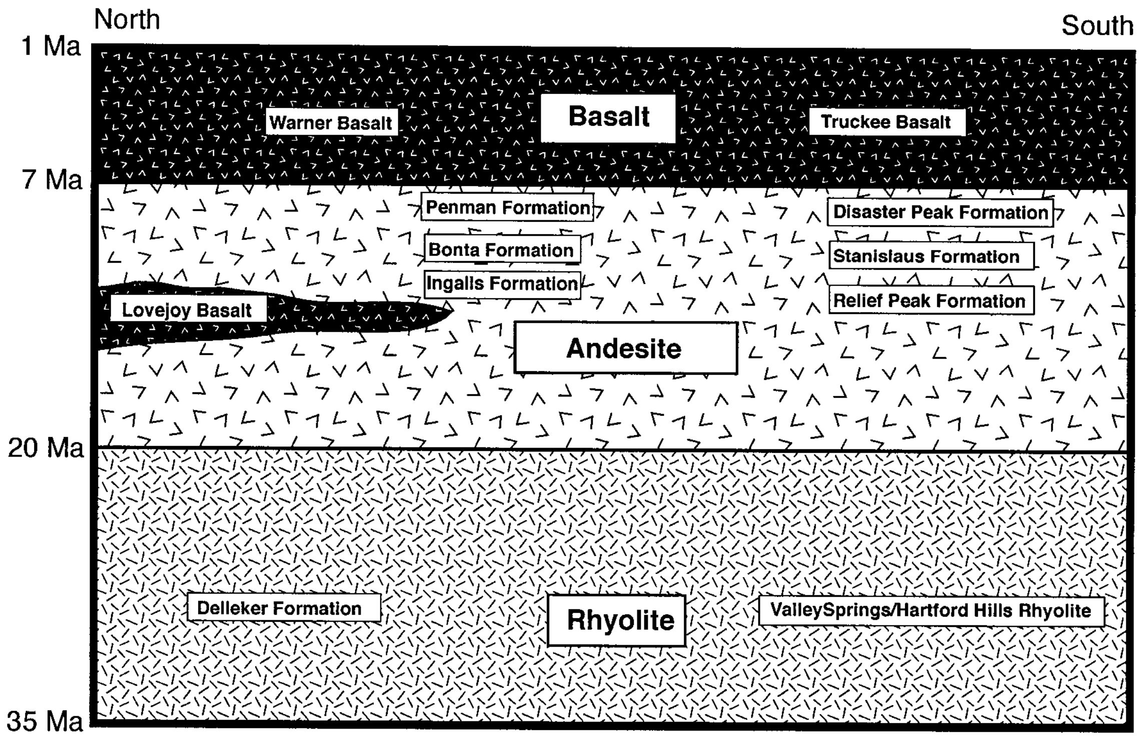

Figure 4. Generalized stratigraphy of the Tertiary volcanic rocks in the Sierra Nevada (after Durell, 1959; Slemmons, 1966; and Wagner et al., 2000). Formation names are shown schematically; formations are in the correct stratigraphic order but lateral correlations are not known. The Hartford Hills Rhyolite and Valley Springs Formations are age equivalent (Dalrymple, 1963).

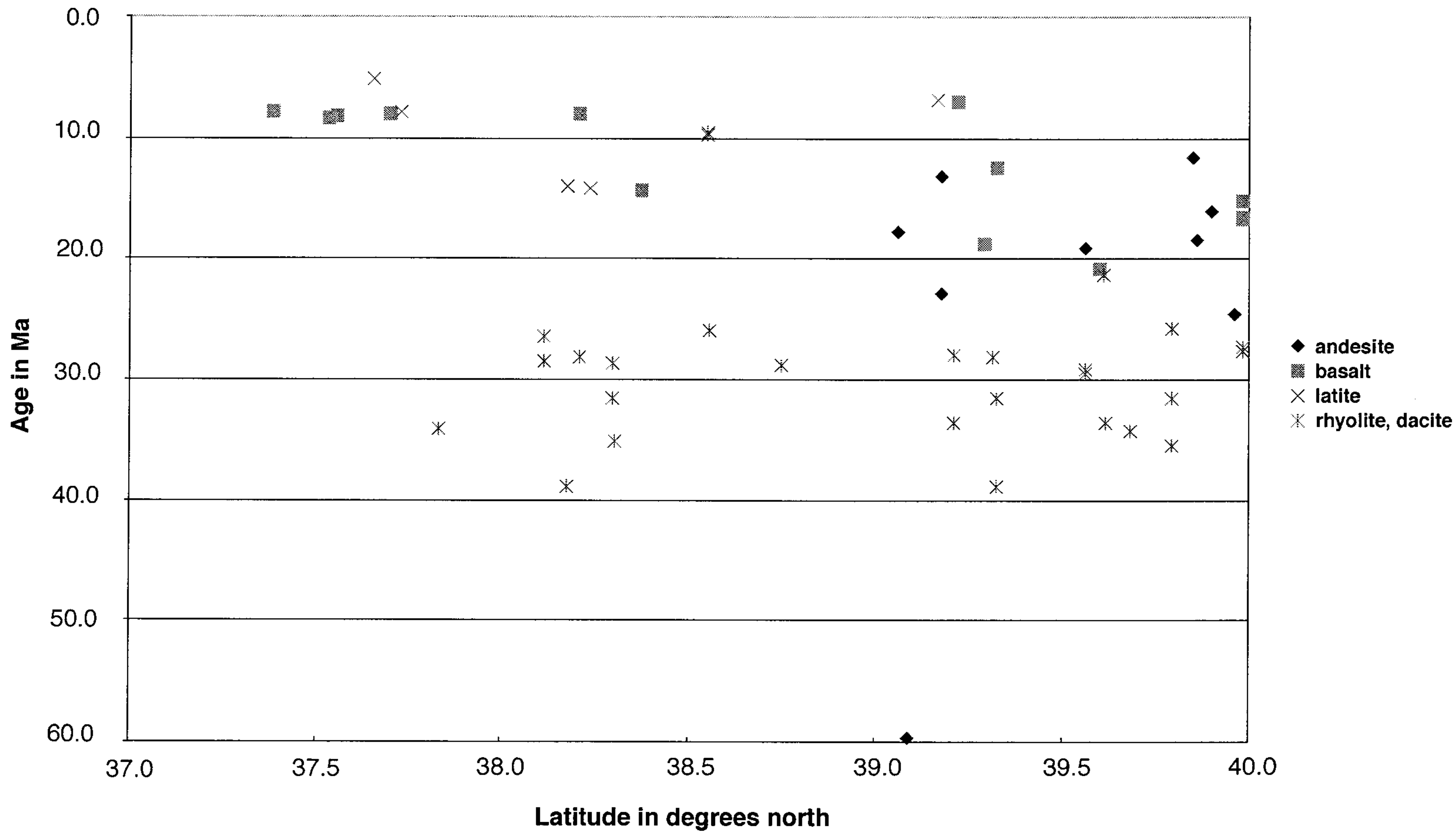

Figure 5. Ages and latitudes of Sierra Nevada volcanic rocks. K/Ar and Ar/Ar ages are from Dalrymple (1963), Durell (1987), Wagner and Saucedo (1990), Saucedo et al. (1992), Page et al. (1995).

Table 1. AGES OF VOLCANIC ROCKS IN THE SIERRA NEVADA

Sample Name	Rock Type	Age (in Ma)
Penman	andesite	6.8
gjs 100-84	andesite	8.4 *
Ingalls	andesite	11.3
dlw 17-85	andesite	13.0 *
Penman	andesite	13.6
stm-3a	andesite	14.4 *
gjs 2-85	andesite	18.0
Bonta	andesite	19.7 #
KA 1253	andesite	54.9
KA 1096	basalt	2.3
KA 1102	basalt	2.4
KA 1093	basalt	3.0
KA 1092	basalt	3.2
KA 1103	basalt	3.2
KA 1070	basalt	3.3
KA 1071	basalt	3.3
KA 1187	basalt	3.4
KA 1077	basalt	3.6
KA 1186	basalt	3.6
KA 1109	basalt	7.6
KA 969	basalt	9.5
KA 1073	basalt	10.4
Warner	basalt	11.4 **
KA 994	basalt	11.8
KA 1075	basalt	11.9
KA 1076	basalt	14.0
Lovejoy	basalt	16.0 ##
stm-1	dacite	24.7
KA 1167	latite	0.4
KA 1078	latite	1.2
KA 1094	latite	1.3
KA 1097	latite	2.0
KA 1135	latite	3.1
KA 1110	latite	9.2
KA 1124	latite	9.4
KA 1120	rhyolite	4.8
KA 1119	rhyolite	4.9
KA 1098	rhyolite	16.5
KA 1126	rhyolite	21.0
KA 1121	rhyolite	21.2
KA 1101	rhyolite	21.7
KA 1072	rhyolite	22.5
KA 1234	rhyolite	22.8
KA 1130	rhyolite	23.2
KA 1129	rhyolite	23.4
KA 1132	rhyolite	23.4
KA 1123	rhyolite	23.7
KA 1163	rhyolite	23.9
KA 1128	rhyolite	24.0
KA 1191	ryholite	24.4
KA 1235	rhyolite	26.7
KA 975 A	rhyolite	26.8
KA 1127	ryholite	26.8
KA 1200	rhyolite	28.8
KA 1202	rhyolite	28.8
KA 999	rhyolite	29.3
KA 1133	ryholite	29.5
KA 1011	rhyolite	30.3
KA 1190	rhyolite	30.7
KA 1131	rhyolite	34.1
KA 1122	ryholite	34.1

*Wagner and Saucedo, 1990
Durell, 1987
**Saucedo et al., 1992
##Page et al., 1995
All other data from Dalrymple, 1964

sample by the presence of monocrystaline quartz (Slemmons, 1966), whereas the Delleker contains both quartz and biotite (Durrell, 1959).

The next period of volcanic activity was characterized by the eruption of andesitic material. Slemmons (1966) noted that phenocrysts in the lower andesites are predominantly pyroxenes and that the upper andesitic units contain a greater abundance of hornblende. To the north of Donner Pass are the pyroxene andesite deposits of the Ingalls Formation (Durrell, 1959). Overlying the Ingalls Formation are the hornblende andesite Bonta and Penman formations. South of Donner Pass, the pyroxene andesites of the Relief Peak and Stanislaus formations (Slemmons, 1966) are overlain by the Disaster Peak Formation, which contains hornblende andesite (Fig. 4).

All of the andesitic units, especially in the central Sierra Nevada, are often grouped together and referred to as the Mehrten Formation (Wagner and Saucedo, 1990). Volcaniclastic andesitic rocks in the western foothills deposited in a fluvial setting were named the Mehrten Formation by Piper et al. (1939). At its type locality near Comanche Reservoir (Fig. 2), the Mehrten is composed of andesitic sandstone and conglomerate. The Mehrten Formation in its broader sense also encompasses the Ingalls, Relief Peak, Stanislaus, Bonta, Penman and Disaster Peak rocks. The rocks composing the Mehrten under this broader usage include necks, plugs, proximal volcanic deposits, and fluvially transported andesitic material. Andesitic volcanism seems to have started at about 19.7 Ma (Durrell, 1987) and to have lasted until about 6.8 Ma (Wagner and Saucedo, 1990) (Fig. 5).

Contemporaneous with the andesitic volcanism was the eruption of the Lovejoy Basalt in the northern Sierra (Figs. 4, 5). The Lovejoy is an olivine basalt (Durrell, 1959) that crops out in an area 5 to 50 km wide north of Donner Pass (Fig. 2). The

Lovejoy is correlative with the Putnam Peak Basalt in the Coast Ranges (Fig. 3), which lies 240 km southwest of the Lovejoy type locality (Siegle, 1988). The Putnam Peak Basalt at its type locality is unconformably overlain by the Neroly Formation (Siegel, 1988). Dates from flows at the base of the Lovejoy show that it was erupted at approximately 16 Ma (Page et al., 1995).

The last phase of volcanism in the Sierra was dominated by basalt. These rocks include the Warner and Truckee basalts (Fig. 4) but also include some rhyolites and latites. This last phase of volcanism lasted from 7 Ma to 1 Ma (Fig. 5).

Tertiary arc-related volcanism in the Sierra Nevada does not appear to have occurred south of the Merced River drainage (Fig. 2). Not only are there no outcrops composed of Miocene volcanic rocks south of the Merced River drainage, there also are no Miocene or Pliocene sedimentary units along the flanks of the southern Sierra that contain significant volcaniclastic sediment (Bartow, 1995).

Coast Ranges Lithology and Stratigraphy

The Coast Ranges are the closest and the volumetrically largest source terrain for the clasts in the Kirker Formation and the San Pablo Group. Mesozoic rocks in the Coast Ranges include the Franciscan Complex, the areally less extensive Coast Range Ophiolite, and the Great Valley Group. The Mesozoic rocks are in turn covered by Paleocene and Eocene sedimentary rocks. Upper Tertiary sedimentary and volcanic units rest unconformably on all of the above (Jennings et al., 1977). West of the San Andreas fault (Fig. 2), plutonic and metamorphic rocks of the Salinian Block also are present.

Franciscan Complex

The Franciscan Complex is composed predominantly of graywacke showing varying degrees of metamorphism. Other diagnostic lithologies in the Franciscan include blueschist and red and green chert. Franciscan conglomerates contain locally derived graywacke, blueschist, and red chert, as well as black chert and plutonic, volcanic, and metavolcanic rocks derived from the Sierra Nevada (Seiders and Blome, 1988).

Coast Range Ophiolite

The Coast Range Ophiolite is volumetrically insignificant compared to the Franciscan Complex and the Great Valley Group. However, the Coast Range Ophiolite contains several diagnostic rock types near its base. The lower portions are composed of diabase, gabbro, peridotite and serpentinite; the upper portions contain metasandstones and metavolcanic rocks (Blake et al., 1984).

Great Valley Group

The Great Valley Group is a forearc-basin assemblage composed of conglomerate, sandstone, and shale resting conformably on the Coast Range Ophiolite and structurally on the Franciscan. The basal portions of the Great Valley Group exhibit varying degrees of metamorphism, whereas the upper portions are unmetamorphosed. Locally the Great Valley Group contains conglomerate composed of the same kinds of Sierran clasts found in the Franciscan as well as clasts of the Franciscan itself. No diagnostic Great Valley rock types can be recognized in the field (Seiders and Blome,1988).

Paleocene and Eocene Rocks

Paleocene and Eocene rocks present in the area are composed mostly of quartzofeldspathic sandstone and shale (Graymer et al., 1994).

Monterey Rocks

In the east Bay area, the Miocene Monterey Group consists of chert, shale, and sandstone. The diagnostic rock of the Monterey Group is laminated light-brown chert. In other places, the Monterey is a ranked as a formation and contains phosphatic rocks, which are unique to this unit (Hill, 1979).

Coast Range Volcanic Rocks

Volcanic rocks occur in the Coast Ranges at several different volcanic centers. The centers that are geographically and chronologically relevant to this study are Burdell Mountain, Donnell Ranch, Berkeley Hills, and Quien Sabe (Fig. 3). The rocks at these locations are composed largely of light gray basalt, biotite-bearing andesite, and very sparse rhyolite (Graymer et al., 2002). Because they have similar ages and chemistry, these units may represent a single volcanic center (McLaughlin et al., 1998; Wakabayashi, 1999; Graymer et al., 2002). If so, the volcanic center has, since its eruption at approximately 10 Ma, been dissected by right-lateral slip on dextral faults in the eastern Bay area (McLaughlin et al., 1998; Wakabayashi, 1999; Graymer et al., 2002).

Other volcanic units in the area, including the Sonoma Volcanics, Clear Lake Volcanics, and Concord Basalt (Fox et al., 1985; Sullivan et al., 1995a), are too young to have contributed clasts to the conglomerate units in this study.

Salinian Plutonic and Metamorphic Rocks

The Salinian block, located west of the San Andreas fault (Fig. 2), contains granitic plutons, metamorphic rocks, and Tertiary rocks that are distinct from those east of the San Andreas fault. Granitic rocks may underlie the northern California borderland (Jachens et al., 1998), suggesting that granitic rocks lie to the north of Point Reyes and are presently submerged off the coast. These granitic rocks may have been exposed at the latitude of the Bay area during the Miocene.

Other Tertiary Basin Deposits

Some sedimentary clasts found in this study could have been derived from other uplifted sedimentary basins, such as those associated with the Quien Sabe and Burdell Mountain volcanic centers. These sedimentary rocks look similar to the Miocene sedimentary rocks of the San Pablo Group (R. Graymer, personal commun., 2001).

Stratigraphy of the Greater East Bay Area

For the purposes of simplicity and clarity, the nomenclature used in this paper for the units in the east Bay area will follow that used by Graymer et al. (1994), who also provided the most detailed and consistent map of the study area. This nomenclature is used as a starting point to compare and contrast the stratigraphy of the different study areas. The lithologic units addressed in this study (Fig. 6) have been assigned ages from Oligocene to Pliocene. Not all of the units in this study are represented at every locality. Graymer et al. (1994) mapped the Cierbo and the Briones formations together in only one location on the southern shore of San Pablo

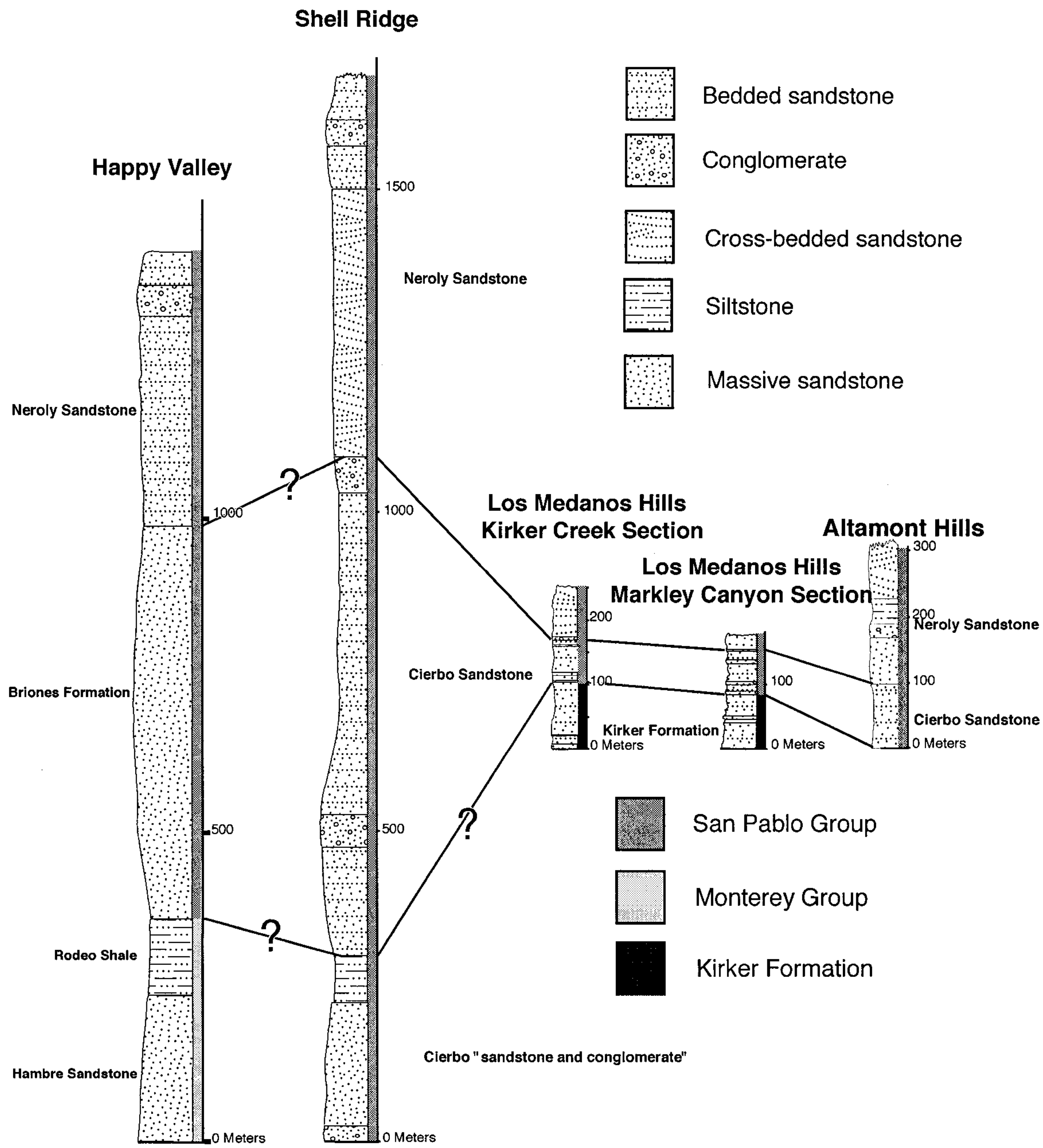

Figure 6. Composite stratigraphic sections of the Kirker Formation, Monterey Group (Hambre Sandstone and Rodeo Shale), and San Pablo Group (Cierbo Sandstone, Cierbo "sandstone and conglomerate," Briones Formation, and Neroly Sandstone). Queried contacts denote uncertain stratigraphic relationships. Unit thicknesses for Happy Valley are from Graymer et al. (1994), Shell Ridge from Walker et al. (1996), Los Medanos Hills from Sullivan et al. (1995b), Altamont Hills from Lamarre et al. (1993).

Bay; over much of the study area, only one or the other of the formations is present.

In a regional analysis of the Monterey, San Pablo, and Contra Costa groups, Graham et al. (1984) concluded that arc-derived andesitic debris was deposited on an early to middle Miocene shelved forearc. The middle Miocene onset of strike-slip due to the evolving San Andreas fault system led to interfault block segmentation, forming local basins. This led to a complex sedimentation pattern distinguished by the addition of a forearc provenance consisting of sedimentary-metasedimentary and volcanic-metavolcanic detritus. The waning of arc volcanism caused the deposition of andesitic debris to cease.

Kirker Formation

The Kirker Formation unconformably overlies the Eocene Markley Formation along a regional unconformity (Sullivan et al., 1995b). The Kirker Formation is restricted to the area east of the Kirker Pass fault on the northeast flank of Mount Diablo. The Kirker at its type section is approximately 95 m thick, and it has a 9-m-thick basal conglomerate interpreted to represent a fluvial environment (Sullivan et al., 1995b). Most of the Kirker is composed of marine sandstone, the upper 43 m of which are tuffaceous. The Kirker was assigned to the Oligocene by Primmer (1960); however, based on stratigraphic relationships and the composition of the sand, Sullivan et al. (1995b) preferred a Miocene age.

Monterey Group

The upper Miocene Monterey in the east Bay area is ranked as a group. Early maps by Lawson (1914) and Clark (1915) show the Hambre Sandstone and the Rodeo Shale of the Monterey Group in the Los Medanos Hills and at Shell Ridge

(Fig. 1), but none of the localities sampled for the present study were mapped as Monterey Group by Graymer et al. (1994). Lawson (1914) first defined the Monterey Group in western Contra Costa County, and he included the Briones Formation as its uppermost unit. The Briones was later moved to the overlying San Pablo Group by Trask (1922).

The sandstone of the Monterey Group contains about 30% volcanic fragments and 20% plagioclase, mostly andesine (Hill, 1979). The grains are angular to subangular. The environment of deposition was shallow marine to neritic. The Hambre Sandstone and the Rodeo Shale, mapped as the Cierbo "sandstone and conglomerate" of the San Pablo Group (Fig. 6) by Graymer et al. (1994), are Mohnian in age (Hill, 1979).

San Pablo Group

The San Pablo Group (Clark, 1915) orignally consisted of upper (Neroly) and lower (Cierbo) sandstones, which were distinguished mainly on the basis of biostratigraphic criteria. Trask (1922) moved the Briones Formation from the Monterey Group into the overlying San Pablo Group based on faunal similarities. The San Pablo Group dramatically thickens to the west (Fig. 6) across the trend of the Mount Diablo anticline (Sullivan et al., 1995b).

The Briones and Cierbo sandstones are feldspatholithic sandstone units that cannot be consistently distinguished from each other by lithologic characteristics at all their locations and can only be distinguished by biostratigraphic characteristics for limited distances. Wagner (1978) suggested retaining the Briones as a formation and reducing the Cierbo to an informal member of the Briones. The Briones and the Hambre sandstone of the Monterey Group are lithologically indistinguishable in hand sample, at least locally. The Briones and Cierbo are both coastal-marine units except in the eastern Los Medanos Hills, where the Cierbo is fluvial (Sullivan et al., 1995b).

The Neroly contains medium-grained, volcanolithic sandstone. Over most of the study area, the grains are characteristically covered with a montmorillonite clay coating that gives the unit a blue color in outcrop (Lerbekmo, 1961). The Neroly has been correlated across the Sacramento Valley with the Mehrten Formation on the basis of drill hole data (Louderback, 1924). The Neroly contains both fluvial and marine facies in the Los Medanos Hills and at Shell Ridge (Buising and Walker, 1995; Sullivan et al., 1995b). The Neroly is fluvial in the Altamont Hills (Lamarre et al., 1993), and it is coastal marine at Happy Valley (Graymer et al., 1994).

The age of the Briones is constrained by an unnamed tuffaceous layer in the upper portion of the unit with a K/Ar date of 14.5 Ma (Graymer et al., 1994). The Cierbo contains an 11.4 Ma tuff both in the Los Medanos Hills and at Shell Ridge (Sarna and Walker, 1999). The Neroly is constrained by three tuffs in the Los Medanos Hills to be between approximately 11.1 and 9.8 Ma (Sarna and Walker, 1999), but the top of the formation could be younger.

METHODS

Sampling

Conglomerate was sampled at Los Medanos Hills (LMH), Shell Ridge (SR), Happy Valley (HV), and Altamont Hills (AH) (Fig. 7). Where possible, multiple outcrops were sampled for each unit at each area.

The primary method employed to collect the data for this study was point counting of gravel-sized clasts. Additional data that were collected at each of the exposures include lithology, color, sorting, sedimentary structures, and the types of fossils present. Estimates of sandstone composition were made using a hand lens and, in a few cases, by thin-section analysis. Outcrops were also examined to determine if clasts display a preferred orientation.

About 400 pebbles and cobbles in each of the conglomerate outcrops were studied using a sampling technique designed to approximate taking a disaggregated bulk sample. In order to check if clast size is related to composition, clasts were seperated into the phi size ranges corresponding to pebbles and cobbles (between 4 and 256 mm) of the Udden-Wentworth scale (Boggs, 1987). Size segregation was accomplished by measuring the apparent long axis of each clast in outcrop view. The apparent long axis generally corresponds to the true medial axis (Kellerhals et al., 1975). Furthermore, Kellerhals and Bray (1971) showed that measurements of the apparent long axis are similar to the results obtained by sieving

Counting was done by ribbon sampling, which entails the delineation of an area that is at least several times greater than the largest clast size sampled and counting all the relevant clasts in that area (Howard, 1993). At each outcrop, several areas were defined on the outcrop face, usually encompassing between 25 and 100

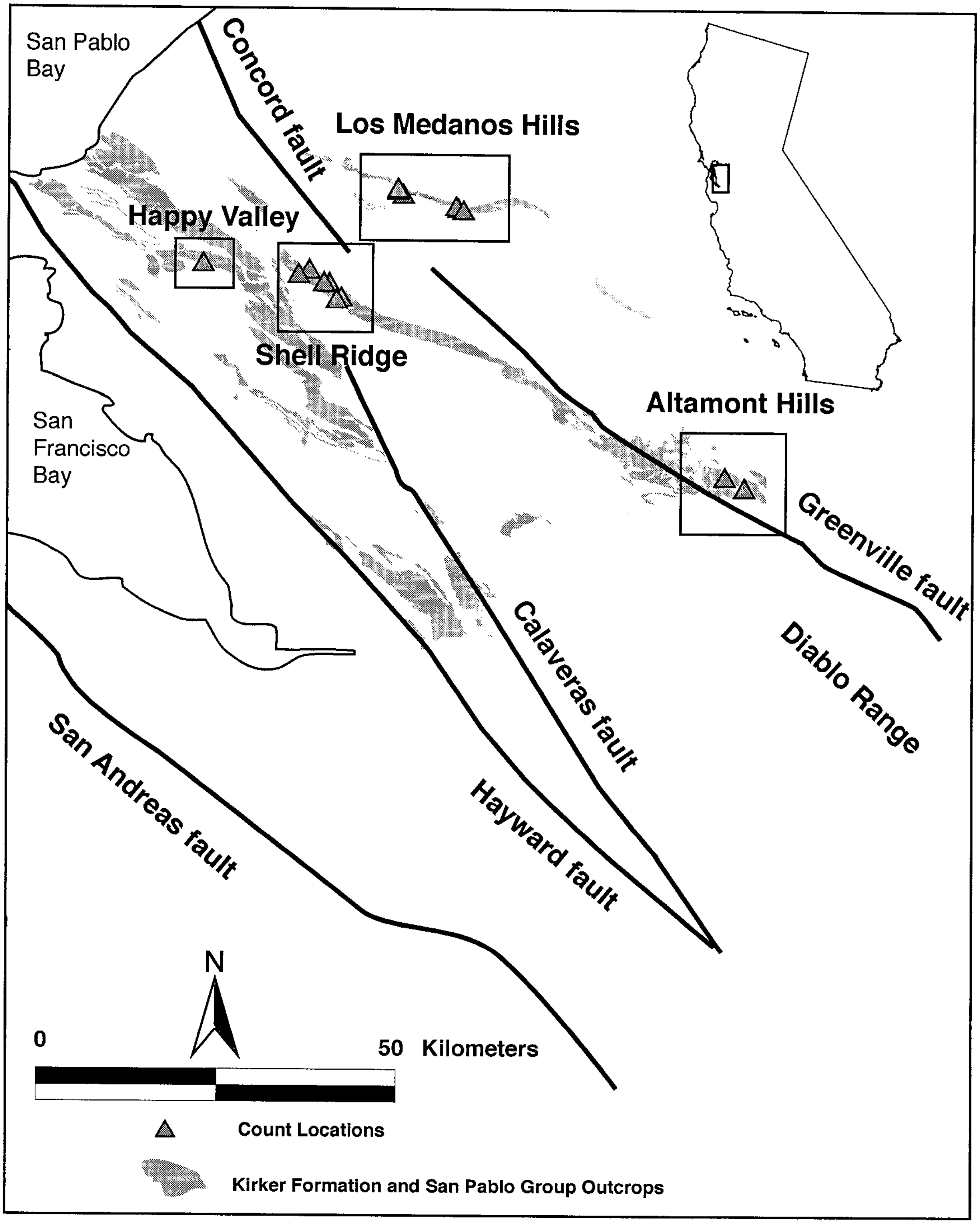

Figure 7. Thesis study areas (boxes) and count locations (triangles) showing some major faults and the outcrop pattern of the Kirker Formation and the San Pablo Group (after Graymer et al., 1994).

clasts, and several subareas were counted for a total of approximately 400 clasts. This allowed comparisons of clast size and compositions between subareas so that outcrop variability could be judged. Clasts were discarded if they could not be identified or showed evidence of postdepositional fracturing such that the original clast morphology could not be determined.

Clast counts are subject to sampling and analytical error; combined, these yield the total probable error (Howard, 1993). The sampling error is a function of the location on the outcrop and the homogeneity of the deposit. The analytical error is due to misidentification of clasts and miscounting. If error associated with clast identification is negligible, then the analytical error is equal to the counting error. If the clast population is evenly distributed, the sampling error is negligible and the sample is representative of the total population. To check that the sample population is representative of the total population, subsets of the sample population were counted and compared as suggested by Howard (1993).

Clasts were classified into several broad categories: volcanic, sedimentary with separated red chert and black chert subpopulations, and metamorphic with a separated metavolcanic subpopulation. Vein quartz was counted as a separate category. Special attention was paid to the volcanic clast types, which were counted as individual subpopulations based on variations in the groundmass color or texture or the types of phenocrysts present. Sedimentary clasts include sandstone, siltstone, mudstone, porcellanite, and chert. Red and black chert were counted separately because red chert has a Coast Range source and black chert ultimately has a Sierran source (Murchey et al., 1983), although some black chert is likely to be reworked from conglomerate in the Franciscan Complex and the Great Valley Group. Clasts that were categorized as metamorphic include the subpopulation of metavolcanic clasts and "other metamorphic" clast types, which include graywacke, quartzite, argillite, phyllite, slate, schist, eclogite, and serpentinite. Metavolcanic clasts were recognized by relict volcanic features. The ratio of metavolcanic clasts to total metamorphic clasts is calculated by metavolcanics / metavolcanics + other metamorphics; vein quartz is not included in this calculation.

In places a more specific nomenclature was used to denote the presence of significant clast types such as graywacke and blueschist, where they were recognized.

Estimates of Stratigraphic Thickness

Unit thickness at Shell Ridge was measured using maps, because the units there are nearly vertical, and thus no correction for dip was necessary. The dip at Happy Valley was used with measured map distance to calculate thickness there. Unit thicknesses for the Altamont Hills and the Los Medanos Hills were taken from previous literature (Lamarre et al., 1993; Sullivan et al., 1995b).

Paleocurrent Data

Paleocurrent data were derived either from clast imbrication or, where visible, from cross-stratification. The vector resultant of the paleocurrent directions was then calculated after the methods employed in Picard and Andersen (1975). No corrections for dip were made because dips at LMH and AH are gentle enough to have no effect on the result. Dips at SR are very steep (80-100 degrees) but uncorrected paleocurrent directions are almost perpendicular to strike and so correction is considered to be unnecessary.

Sierran Localities

In addition to the data collected at the four thesis locations in the east Bay area, reconnaissance work was done in the Sierra Nevada and its foothills. The locations were chosen to include the major Sierran volcanic units. Transects were conducted through the Sierran Tertiary volcanics in the Diamond Mountains, near Donner Pass, near Comanche Reservoir, and along the Stanislaus River drainage (Fig. 8). Representative collections of volcanic rocks were made in the Sierra Nevada, and the rocks were identified using a handlens based on their color and mineralogy.

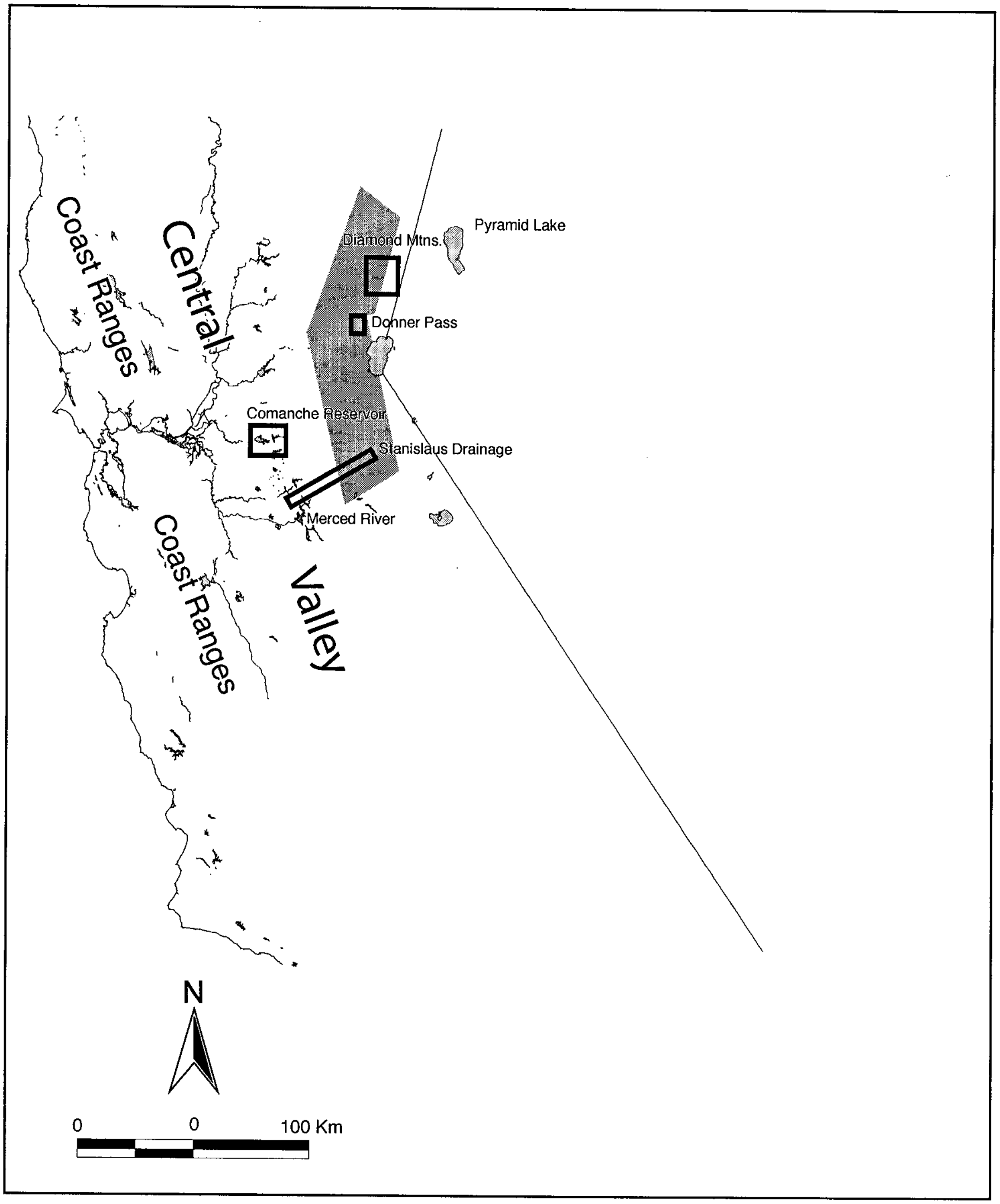

Figure 8. Map of California showing sample transects (in boxes) in the Sierra Nevada. Dark gray area shows outcrop area of the Tertiary volcanics.

SAMPLE SECTIONS

At each of the four areas of Tertiary conglomerate outcrops, the units were subsampled at two different locations if suitable outcrops could be found near the same stratigraphic level, yielding a total of 16 separate point counts (Fig. 7).

Sedimentary features and fossils also were described at each site. The sedimentology of the conglomerate outcrops and the enclosing sandstone are described in Appendix A.

Los Medanos Hills

Tertiary rocks in the Los Medanos Hills strike northwest-southeast and dip to the northeast. The section here consists of the Kirker Formation, the Miocene Cierbo Sandstone, and the Miocene Neroly Sandstone (Figs. 9, 10).

Kirker Formation

In the Los Medanos Hills, the Kirker Formation is 104 m thick near Kirker Creek and 70 m thick near Markley Canyon. The Kirker is composed mostly of feldspathic litharenite. The upper portions of the Kirker are tuffaceous and contain marine invertebrate fossils, whereas the lower sandstone is not tuffaceous and contains a basal conglomerate. The basal conglomerate bed can be traced intermittently across the region in stream cuts. The conglomerate is very poorly sorted and clast supported. The two Kirker clast counts (LMH 1 and 7) were done in this basal conglomerate (Fig. 10).

Cierbo Sandstone

In the Los Medanos Hills, the Cierbo Sandstone is about 57 m thick at Kirker

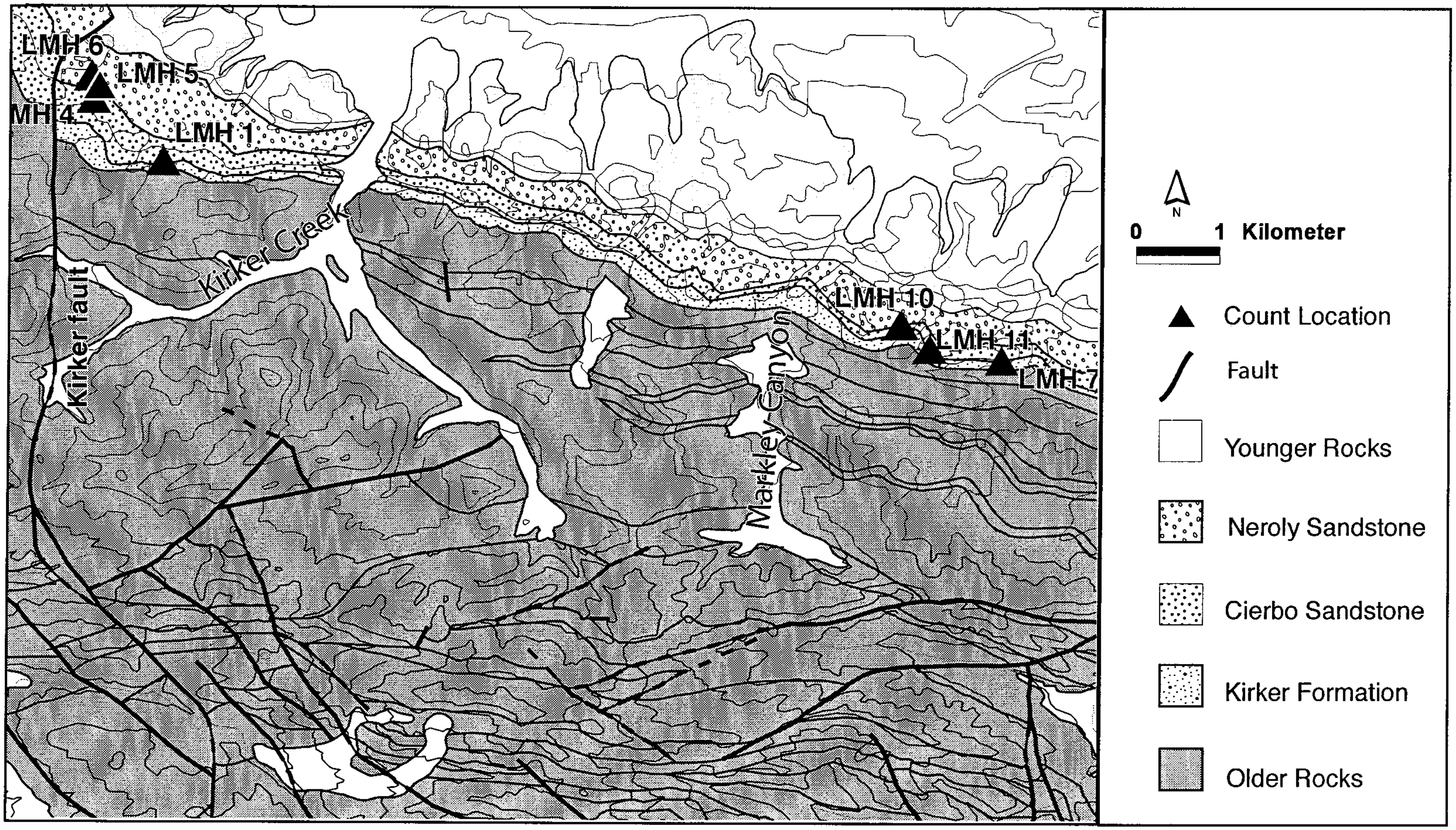

Figure 9. Geologic map of the Los Medanos Hills (after Graymer et al., 1994).

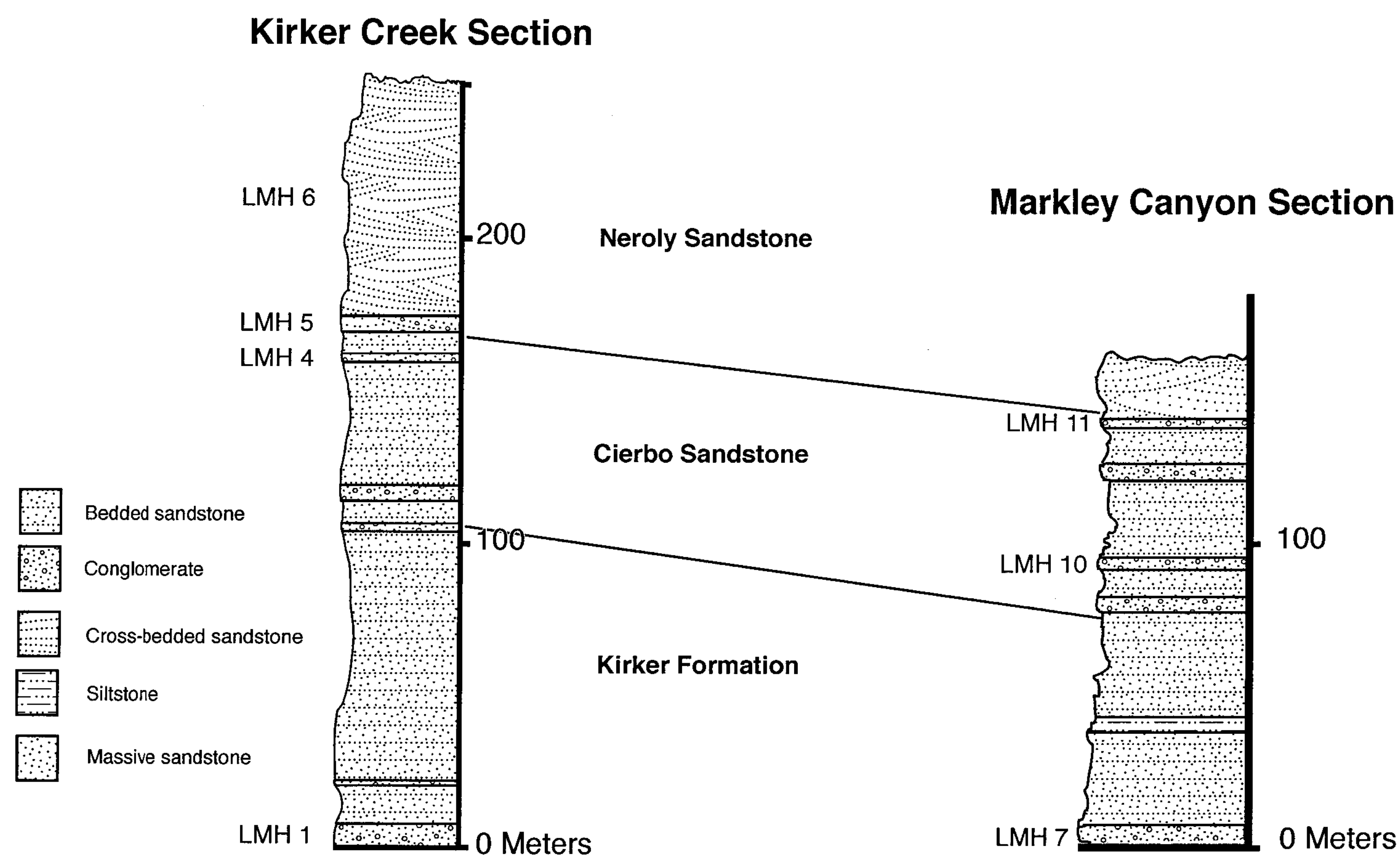

Figure 10. Stratigraphic sections in the Los Medanos Hills at Kirker Creek and Markley Canyon showing only lower portions of Neroly (after Sullivan et al., 1995b) and count locations. LMH 6 is in a conglomerate layer that is too thin to show at this scale.

Creek and 60 m thick near Markley Canyon (Fig. 10). The Cierbo contains conglomerate beds at many stratigraphic levels; none of the beds appears to be regional in extent. The conglomerates that were counted are matrix supported. Many of the conglomerate beds contain varying amounts of shell material including the sand dollar *Astrodapsis*. The Cierbo is composed mainly of feldspathic litharenite similar to that in the Kirker, but near the top of the section it also contains some blue sandstone beds composed of volcanolithic sandstone. Near the top of the Cierbo south of Markley Canyon, one shell hash is composed entirely of *Striostrea? bourgeoissii bourgeoissii* (C. Powell, personal commun., 2001).

Neroly Sandstone

The Neroly at Kirker Creek is about 200 m thick (Sullivan et al., 1995b). Only the lower 80 m were studied in this investigation (Fig. 10). This unit is composed of volcanolithic litharenite with interbedded conglomerate. Two point counts were done in this unit, one at the base of the unit (LMH 5) and the other in the upper trough-cross-bedded portion (LMH 6). Both sampled conglomerates appear to be matrix supported. Both point counts were done in the Kirker Creek region (Fig. 9), because no Neroly conglomerate beds cropout in the Markley Canyon region.

Shell Ridge

This section consists of steeply dipping to overturned beds that form Shell Ridge and several secondary ridges, all of which trend northwest-southeast (Fig. 11). The units exposed here are the Cierbo “sandstone and conglomerate” and the Cierbo Sandstone and Neroly Sandstone of the Miocene San Pablo Group (Fig. 12).

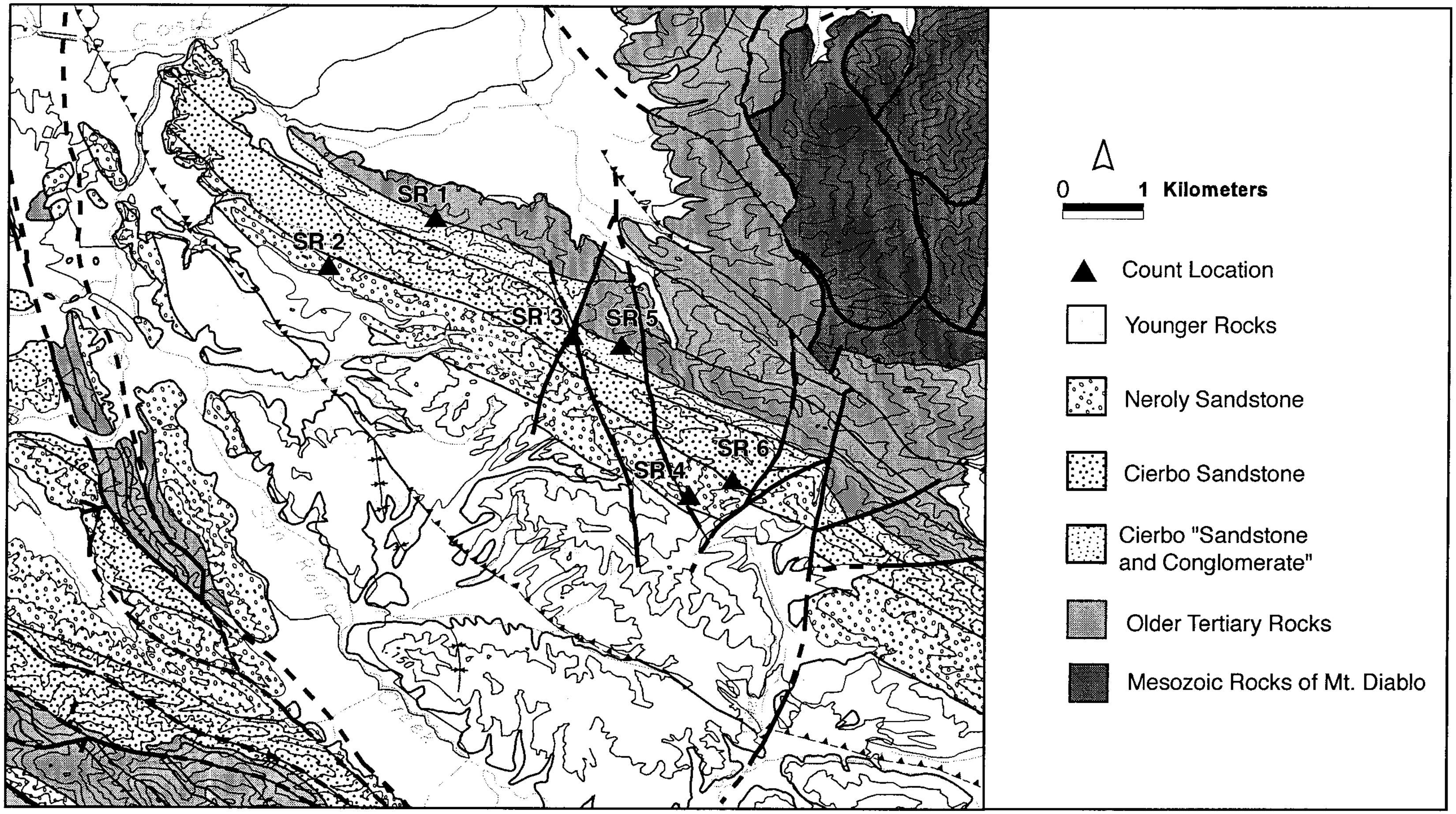

Figure 11. Geologic map of the Shell Ridge area (after Graymer et al., 1994).

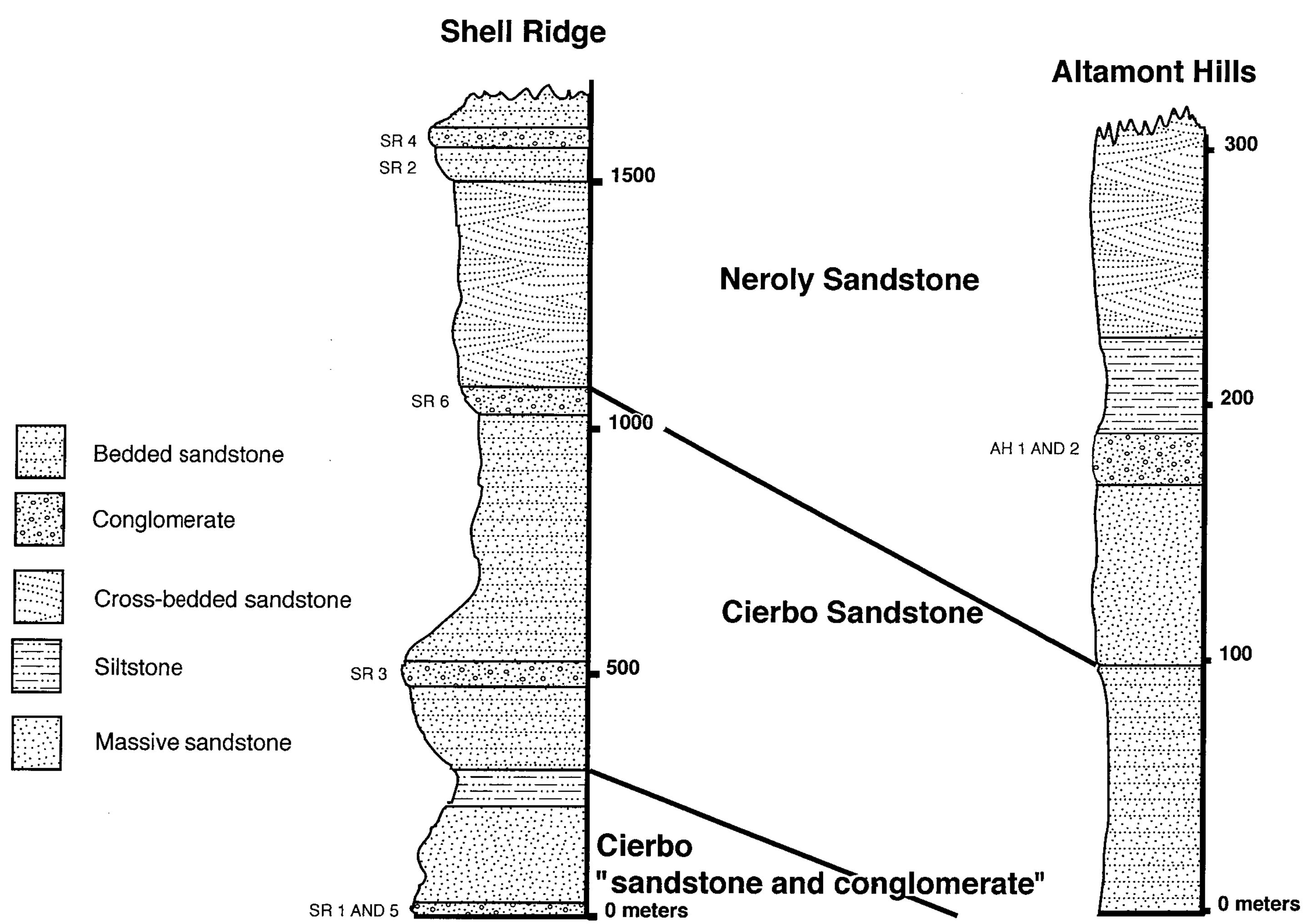

Figure 12. Composite stratigraphic sections in Shell Ridge (after Walker et al., 1996) and Altamont Hills (after Lamarre et al., 1993). The base of the Cierbo is not shown for the Altamont Hills section.

Cierbo "Sandstone and Conglomerate"

Originally mapped as the Hambre Sandstone and the Rodeo Shale by Lawson (1914), these units were mapped by Graymer et al. (1994) as the Cierbo "sandstone and conglomerate" and included by them in the San Pablo Group. This unit is approximately 265 m thick. It is composed mostly of medium- to fine-grained feldspathic litharenite; the lithic fragments and micas give it a salt-and-pepper appearance. A basal conglomerate bed, where the counts were done, can be traced for several kilometers. The conglomerate is matrix supported at SR 1 and clast supported at SR 5. Approximately 5 m above the conglomerate at location SR 1 is an in-life-assemblage composed of the heavy-shelled oyster *Striostrea subtitan* (C. Powell, 2001, written commun.).

Cierbo Sandstone

The Cierbo on the east flank of Shell Ridge is composed mostly of feldspathic litharenite with several lenses of shell hash and conglomerates at different stratigraphic levels. The Cierbo is 762 m thick at Shell Ridge. The shell hashes and conglomerates contain *Striostrea*? *bourgeoissii bourgeoissii*, bivalves, pectinids, and *Astrodapsis* sp. At SR 3, the conglomerate bed is clast supported and contains intercalated shells. The conglomerate at SR 6 is matrix supported.

Neroly Sandstone

The Neroly is 570 m thick and forms a low ridge to the west of Shell Ridge. The lower portion of the section is composed of sandstone with trough cross-beds. The upper section is composed of parallel-bedded sandstone containing shell hashes, and to the south includes lenses of sandstone and conglomerate in rhythmically bedded, fining-upward units. The lower trough-cross-bedded section is missing to the northwest. Both count locations were in the upper shell-rich section. SR 4 is in a matrix-supported, fining-upward sequence. SR 2 is in a matrix-supported, fossil-rich conglomerate. The sandstone that makes up the Neroly here is volcanolithic litharenite.

Altamont Hills

The Miocene section here (Fig. 13) is composed of the Cierbo and Neroly sandstones (Fig. 12). The area is structurally complex, and access is restricted by Lawrence Livermore National Laboratory.

Cierbo Sandstone

In the Altamont Hills, the Cierbo has a maximum thickness of 230 m (Lamarre et al., 1993). The Cierbo is composed of lithic subarkosic sandstone, which is a different composition than at other Cierbo locations. The quartz grains are monocrystalline, and large bleached biotite grains are common. No conglomerate beds were found in this unit.

Neroly Sandstone

In the Altamont Hills, the Neroly is composed of blue volcanolithic litharenite. Both counts were done in the clast-supported conglomerate in the middle of the formation (Fig. 12).

Happy Valley

The section at Happy Valley is composed of the Hambre Sandstone, the

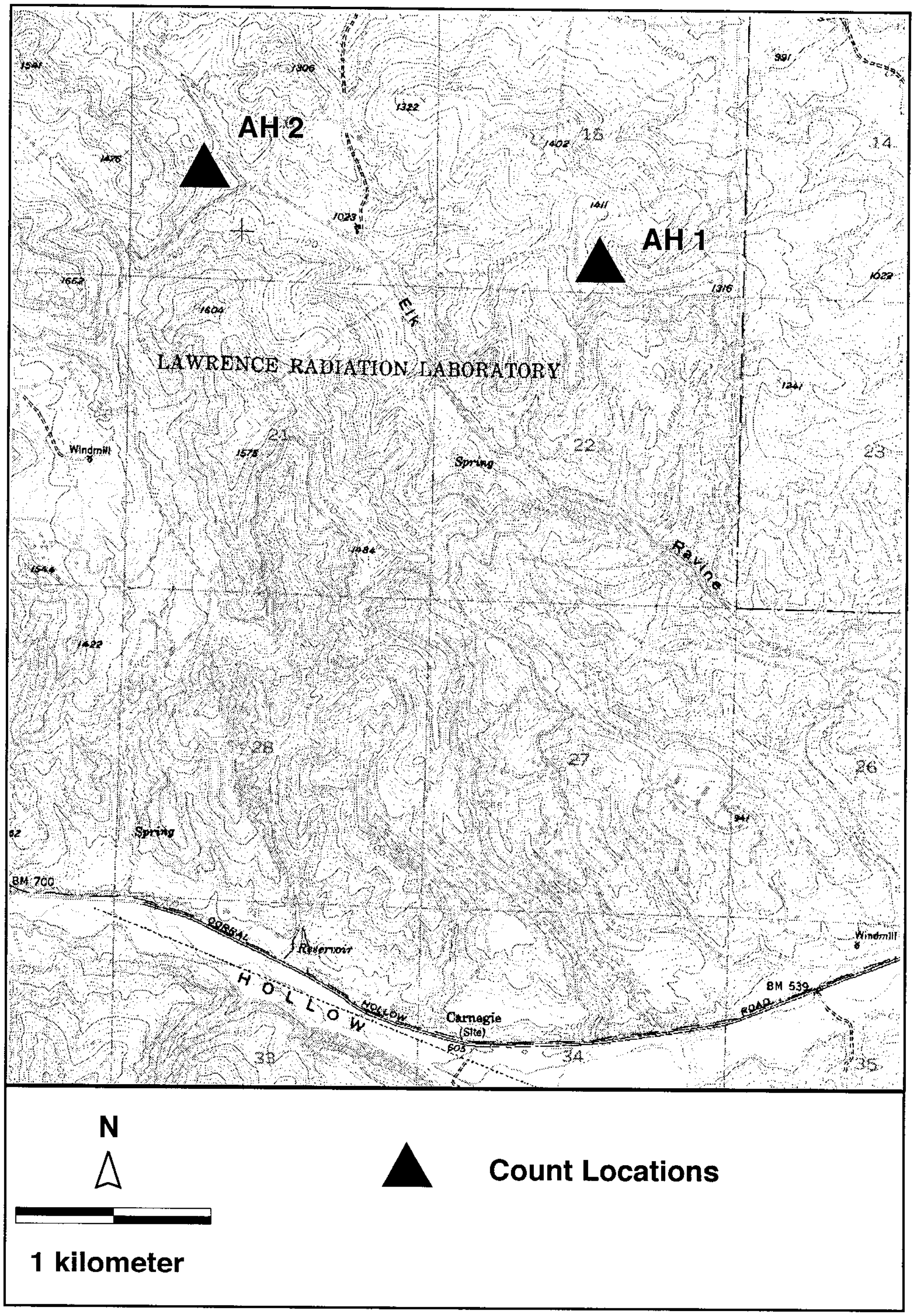

Figure 13. Topographic map of the Altamont Hills, showing the count locations at Lawerence Livermore National Labratory Site 300, from Midway 7.5' quadrangle.

Rodeo Shale, the Briones Formation, and the Neroly Sandstone (Fig. 14). The section was traversed on several different transects but only one conglomerate was found, in the Neroly (Fig. 15). This is the only location west of the trend of the Calaveras fault included in this study, and the Miocene section here is unique in several respects. The Cierbo Sandstone is not present, but the Briones Formation is present. This is the only occurrence of the Briones in this study area (Fig. 6).

Briones Formation

Sandstone of the Briones Formation is composed of feldspathic litharenite. Lenses of shell hash at different stratigraphic levels are common. No conglomerate beds were found in this unit.

Neroly Sandstone

The sandstone of the Neroly is bluish-gray in outcrop; the sandstone is an andesitic litharenite. The fossils include gastropods, thin-shelled bivalves, and plant material, probably reeds.

The count took place in a conglomerate that is divided internally by a 40-cm-thick sand bed. The lower half has parallel bedding 20 to 50 cm thick; the upper half is composed of meter-scale cross-beds. The lower half of the conglomerate is matrix supported and poorly to very poorly sorted. The upper half is clast supported and composed of angular to very angular clasts.

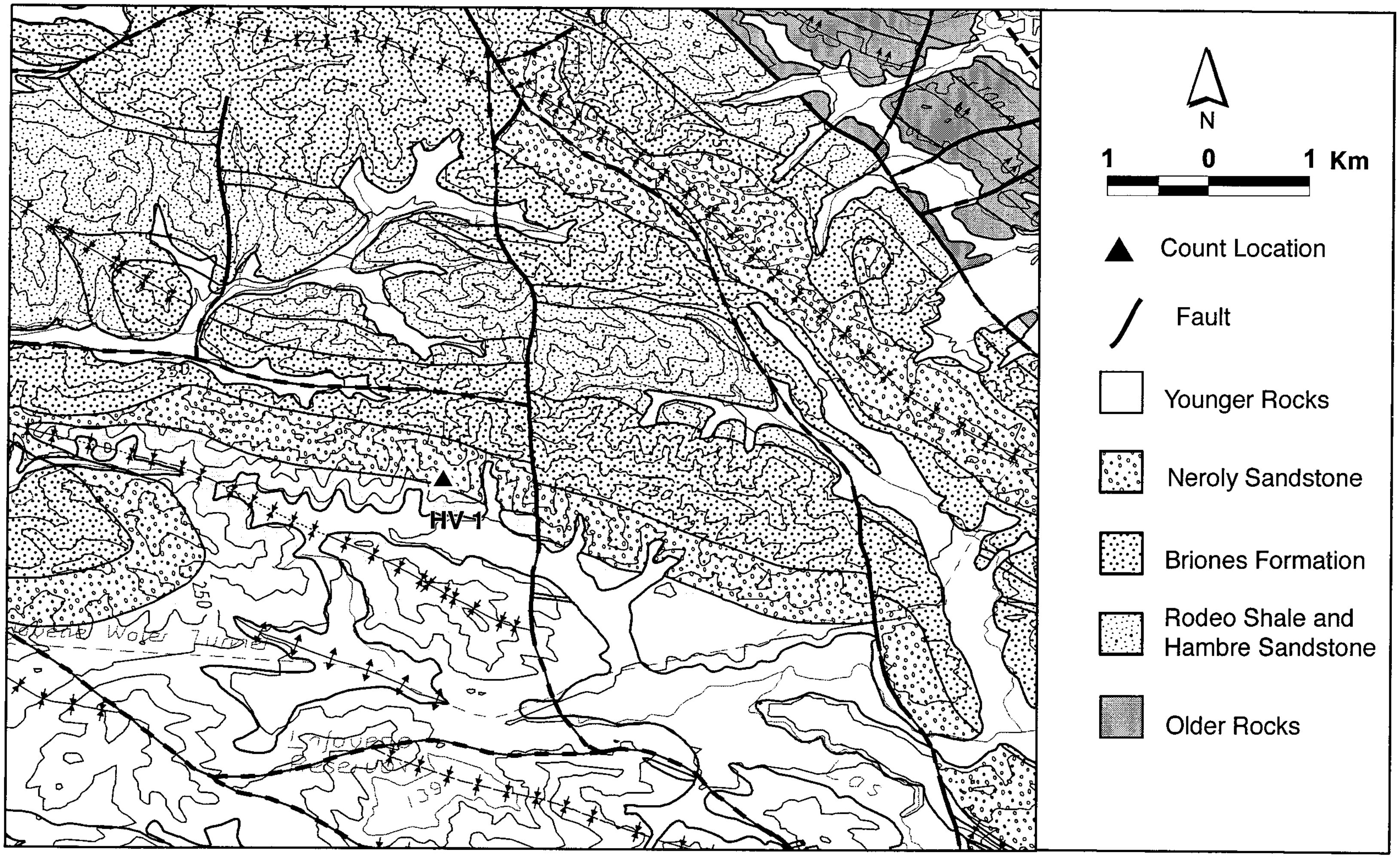

Figure 14. Geologic map of the Happy Valley area (after Graymer et al., 1994).

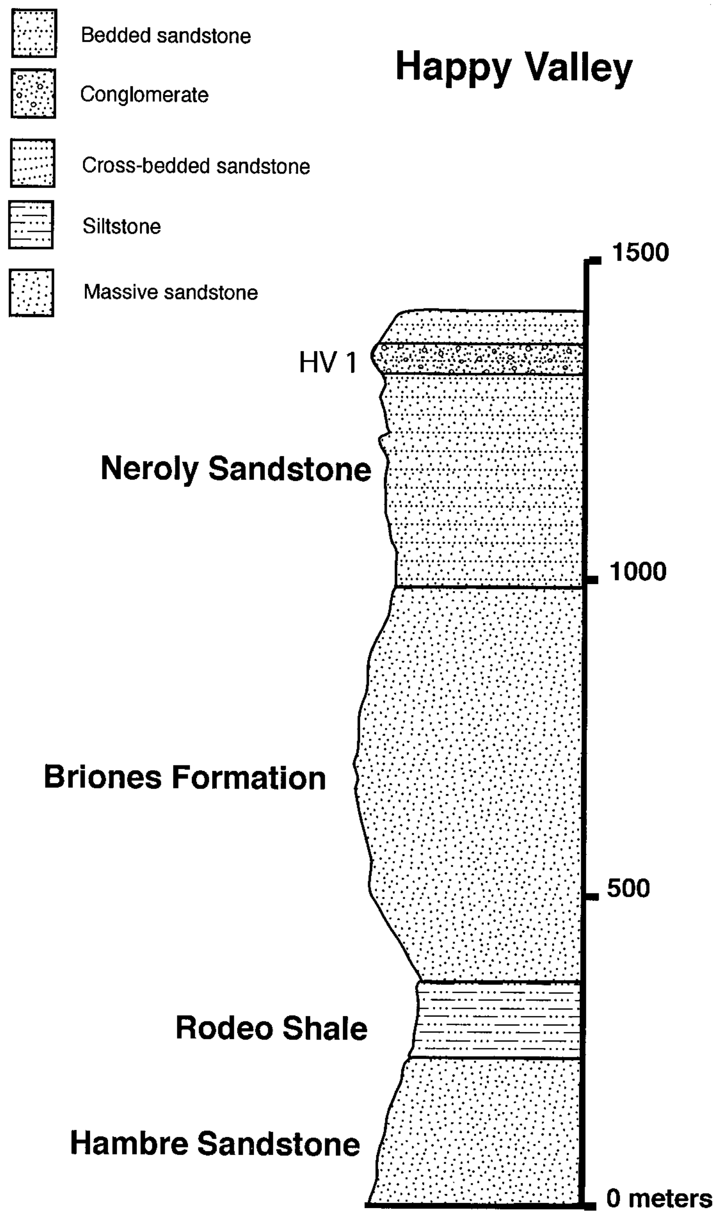

Figure 15. Composite stratigraphic section in the Happy Valley area showing the count location in the Neroly (after Graymer et al., 1994).

RESULTS

Sierran Tertiary Volcanic Rocks

Sierran volcanic rocks can be divided into two separate source regions referred to here as the northern and central Sierran assemblages (Fig. 16). A southern Sierran assemblage is composed of Sierran basement rocks with no volcanic cover.

The northern Sierran area, which extends south from the Diamond Mountains to about the latitude of Donner Pass, is distinguished by the presence of the Lovejoy Basalt and biotite-quartz rhyolite of the Delleker Formation. The central Sierran area extends from Donner Pass south to the Merced River and includes the Donner Pass, Comanche Reservoir, and Stanislaus drainage transects of this study (Fig. 16). This area lacks the Lovejoy Basalt and includes quartz-rhyolite rocks of the Valley Springs Formation and the Hartford Hills Rhyolite, which do not contain biotite.

Both the northern and central source regions include hornblende- and pyroxene-bearing andesites; these rocks may also contain sparse to abundant feldspars. Most andesites have a gray groundmass, but 10-25% have a red groundmass.

Diamond Mountains

Samples of the Delleker Formation were collected from float near its type locality in the Diamond Mountains (Fig. 16). There can be little doubt as to the origin of the float because the Delleker is the only rhyolite in this area. The Delleker clasts are light reddish yellow and contain both quartz and abundant biotite. The andesitic Penman and Ingalls formations are both lahars; the clasts are gray and contain hornblende and pyroxene phenocrysts. The aphanitic, black to dark-brown Lovejoy Basalt was also collected.

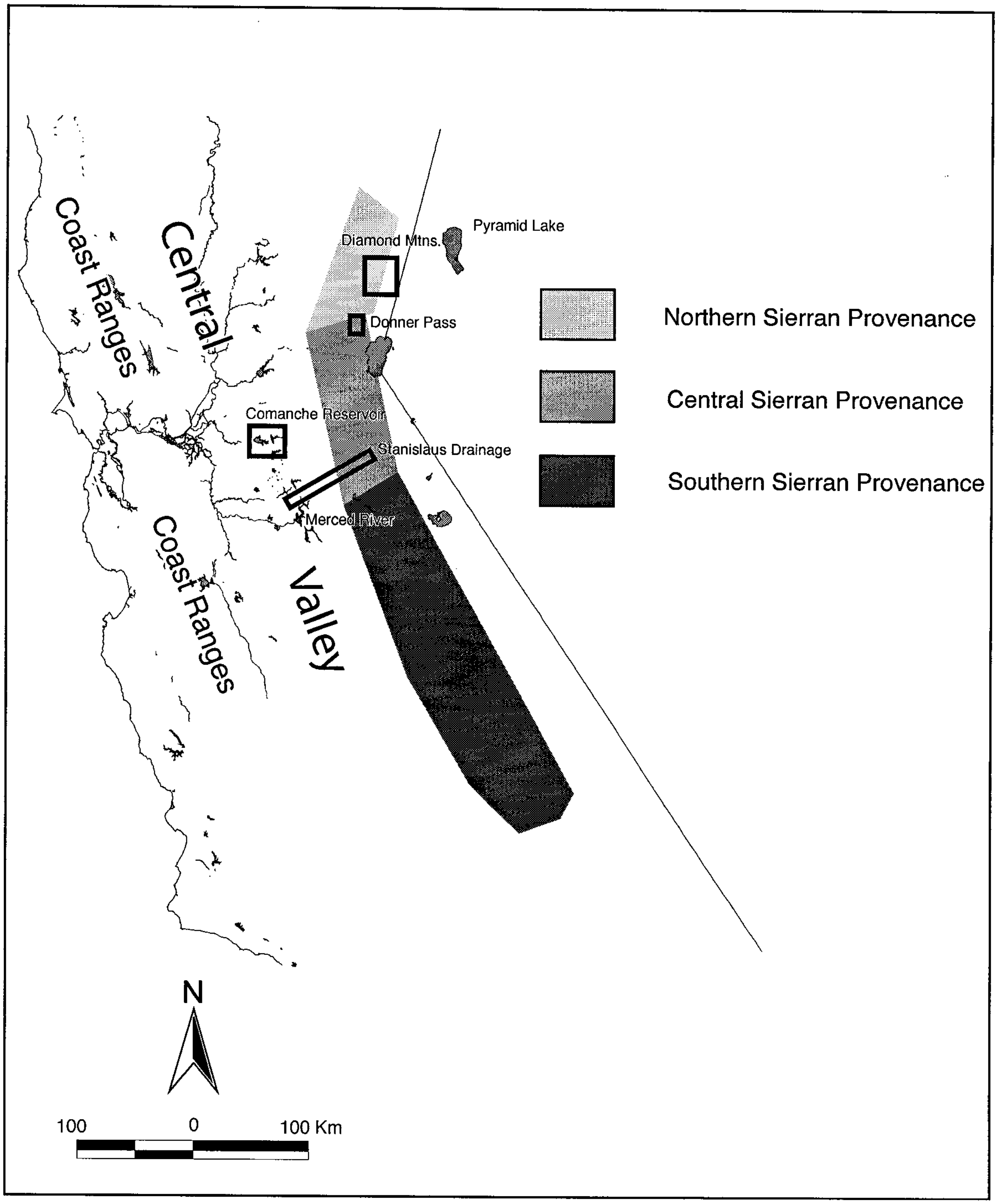

Figure 16. Map of California showing areas of sample transects (in boxes) and the provenance zones in the Sierra Nevada.

Donner Pass

The stratigraphically lowest Tertiary volcanic unit is the Hartford Hills Rhyolite, which is composed of tuffs and flows. The unit was sampled for this study just south of Donner Pass (Fig. 16). The rhyolite at this location contains quartz phenocrysts but lacks biotite and is light reddish yellow. The overlying andesite collected at Donner Pass is a welded tuff; the rock is composed of a gray felsitic matrix with hornblende phenocrysts and pumice lapilli. Other, similar andesites at this location appear to be flows.

Sierran Foothills near Comanche Reservoir

The Valley Springs Formation was sampled near its type locality at Comanche Reservoir (Fig. 16). The Valley Springs is a light-beige, sandy tuff with low-angle cross-beds and interstratified parallel-laminated siltstone beds. The tuff is largely composed of subangular monocrystalline quartz and angular pumice lapilli. Several rhyolitic plugs are nearby, but no proximal rhyolitic deposits were noted. The angularity of the pumice lapilli, however, argues for a short transport distance.

The type locality of the Mehrten Formation now lies beneath Comanche Reservoir, but nearby outcrops of the Mehrten consist of bluish-gray, montmorillonite-coated, andesitic sandstone and conglomerate. On the north side of Comanche Reservoir, the Mehrten contains clast-supported conglomerate with both red and gray andesitic cobbles and hornblende-pyroxene-feldspar andesite clasts. Metamorphic clasts, most of which are quartzite, make up about 10% of the clasts. Some pumice lapilli were also noted.

Stanislaus Drainage

The Stanislaus drainage transect includes the Disaster Peak, Stanislaus, and Relief Peak formations. Rocks encountered were andesitic, ranging from proximal flows and lahars near the Sierran crest to fluvial rocks at lower altitudes. Samples for this study were taken from both flows and lahars.

The andesite clasts sampled along the Stanislaus drainage have a gray groundmass and contain phenocrysts of feldspar, hornblende, and pyroxene. In many of the clasts sampled, feldspar is the dominant phenocryst. At the lower altitudes, where the volcanic units grade into more distal fluvial counterparts, the sand-size fraction has the same bluish-gray clay coating as the Neroly and the Mehrten near its type locality.

Conglomerate Counts

The clast count data are presented in Table 2. Relative proportions of selected clast types are shown in Figure 17. Volcanic clast descriptions are included in Appendix B and summarized in Figure 18. Metamorphic clasts are most common, followed by volcanic clasts; together, they comprise about 80% of the clasts at most locations (Table 2). The metamorphic clasts on Figure 17 are the same as "other metamorphic" clasts in Table 2. Volcanic clasts encountered in this study were categorized as basalt, andesite, and rhyolite, and their relative percentages are presented on ternary plots (Fig. 18).

At several count locations, populations were sorted by clast size to test whether clast compositions varied with grain size. In all cases, no significant differences were noted.

Conglomerate clasts in the Kirker Formation, Cierbo "sandstone and

TABLE 2. PERCENTAGES OF CLAST TYPES IN THE CONGLOMERATE OUTCROPS

Los Medanos Hills							
UNIT NAME	Kirker	Kirker	Cierbo	Cierbo	Cierbo	Neroly	Neroly
LOCATION	LMH 1	LMH 7	LMH 4	LMH 10	LMH 11	LMH 5	LMH 6
Vein Quartz	3.6	11.4	15.3	16.3	12.0	7.6	7.0
Metavolcanic	5.9	26.5	17.3	15.8	23.5	14.8	5.8
Other Metamorphic	19.8	33.9	43.5	47.2	44.5	17.4	9.3
Total Metamorphics	25.8	60.4	60.8	63.1	68.0	32.3	15.0
Basalt	4.1	2.0	5.0	0.3	5.0	28.1	16.5
Andesite	57.7	2.2	15.4	10.1	6.6	12.8	41.5
Rhyolite	6.2	15.6	0.8	2.3	1.3	10.9	17.3
Total Volcanics	68.0	19.8	21.0	12.6	12.8	51.8	75.3
Red Chert	0.0	0.0	0.0	0.0	3.0	0.0	0.0
Black Chert	1.3	5.9	3.0	5.3	3.0	6.3	1.0
Other Sedimentary	1.3	2.5	0.0	2.8	1.3	2.1	1.8
Total Sedimentary	2.6	8.4	3.0	8.0	7.3	8.3	2.8

TABLE 2. PERCENTAGES OF CLAST TYPES IN THE CONGLOMERATE OUTCROPS, CONTINUED

SHELL RIDGE						
UNIT NAME	Cierbo "sandstone and conglomerate"	Cierbo "sandstone and conglomerate"	Cierbo	Cierbo	Neroly	Neroly
LOCATION	SR 1	SR 5	SR 3	SR 6	SR 2	SR 4
Vein Quartz	18.6	7.5	19.0	6.5	6.3	1.0
Metavolcanic	42.6	20.2	25.3	8.5	7.6	0.3
Other Metamorphic	22.6	54.4	30.3	13.5	17.2	0.8
Total Metamorphics	65.2	74.6	55.6	21.9	24.8	1.1
Basalt	0.0	2.6	1.8	0.5	0.0	0.0
Andesite	0.5	8.3	2.5	67.5	63.8	97.5
Rhyolite	1.3	4.7	0.8	0.0	0.0	0.0
Total Volcanics	1.9	15.5	5.0	68.8	63.8	97.5
Red Chert	4.0	0.0	2.8	0.0	1.0	0.0
Black Chert	8.6	0.5	17.8	2.5	4.1	0.5
Other Sedimentary	1.6	1.8	0.0	0.2	0.0	0.0
Total Sedimentary	14.3	2.3	20.6	2.7	5.1	0.5

TABLE 2. PERCENTAGES OF CLAST TYPES IN THE CONGLOMERATE OUTCROPS, CONTINUED

Happy Valley		ALTAMONT HILLS		
UNIT NAME	NEROLY	UNIT NAME	NEROLY	NEROLY
LOCATION	HV 1	LOCATION	AH 2	AH 1
Vein Quartz	10.8	Vein Quartz	0.8	0.5
Metavolcanic	9.0	Metavolcanic	0.8	0.8
Other Metamorphic	74.9	Other Metamorphic	9.5	8.8
Total Metamorphics	84.0	Total Metamorphics	10.3	9.5
Basalt	0.0	Basalt	0.0	0.0
Andesite	0.0	Andesite	89.0	89.5
Rhyolite	0.0	Rhyolite	0.0	0.0
Total Volcanics	0.0	Total Volcanics	89.0	89.5
Red Chert	2.3	Red Chert	0.0	0.3
Black Chert	0.8	Black Chert	0.0	0.0
Other Sedimentary	2.0	Other Sedimentary	0.0	0.3
Total Sedimentary	5.0	Total Sedimentary	0.0	0.5

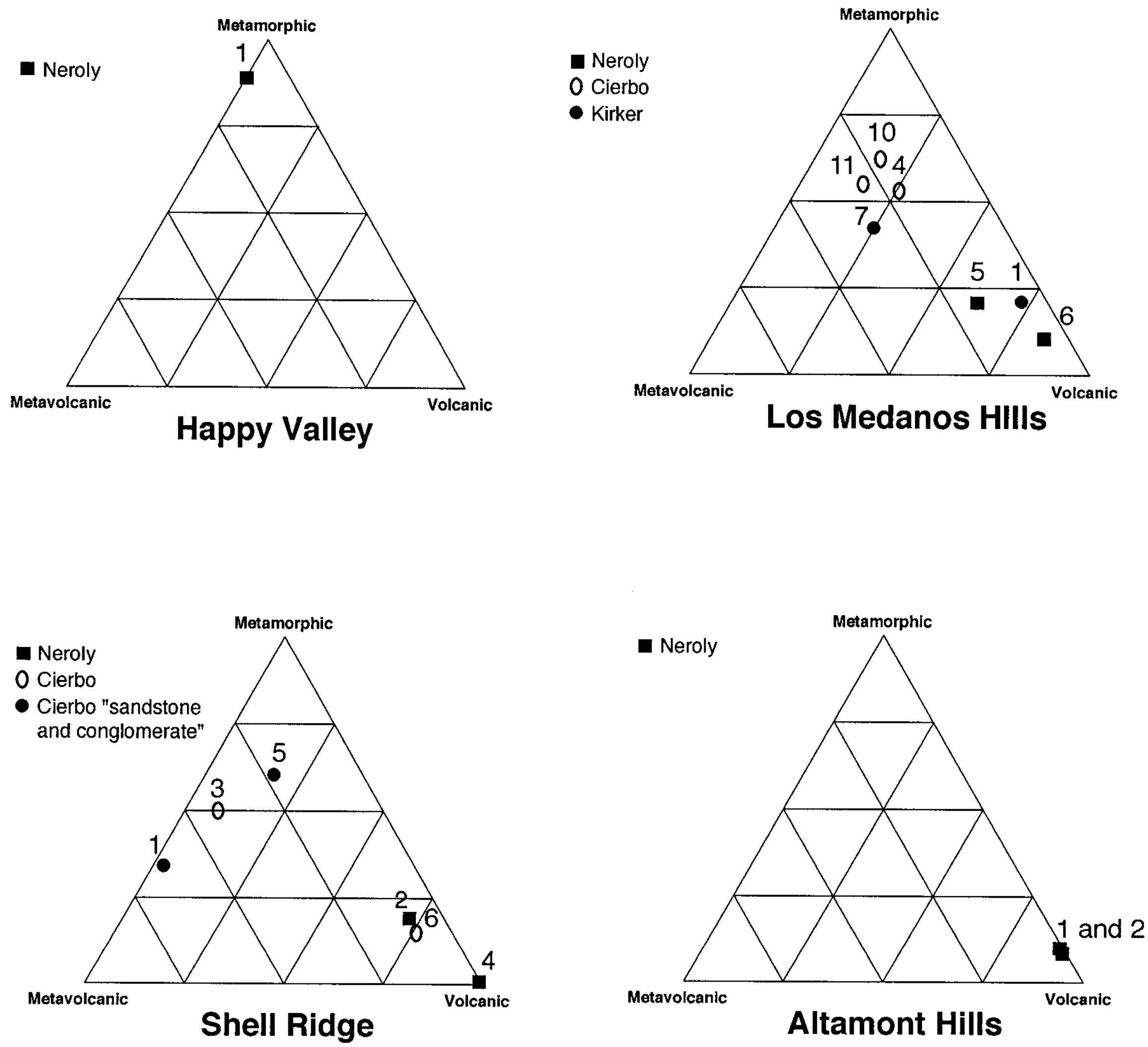

Figure 17. Ternary plots for conglomerate count locations showing relative proportions of metavolcanic rocks, metamorphic rocks ("other metamorphic" in Table 2), and volcanic rocks; numbers on plots refer to location numbers.

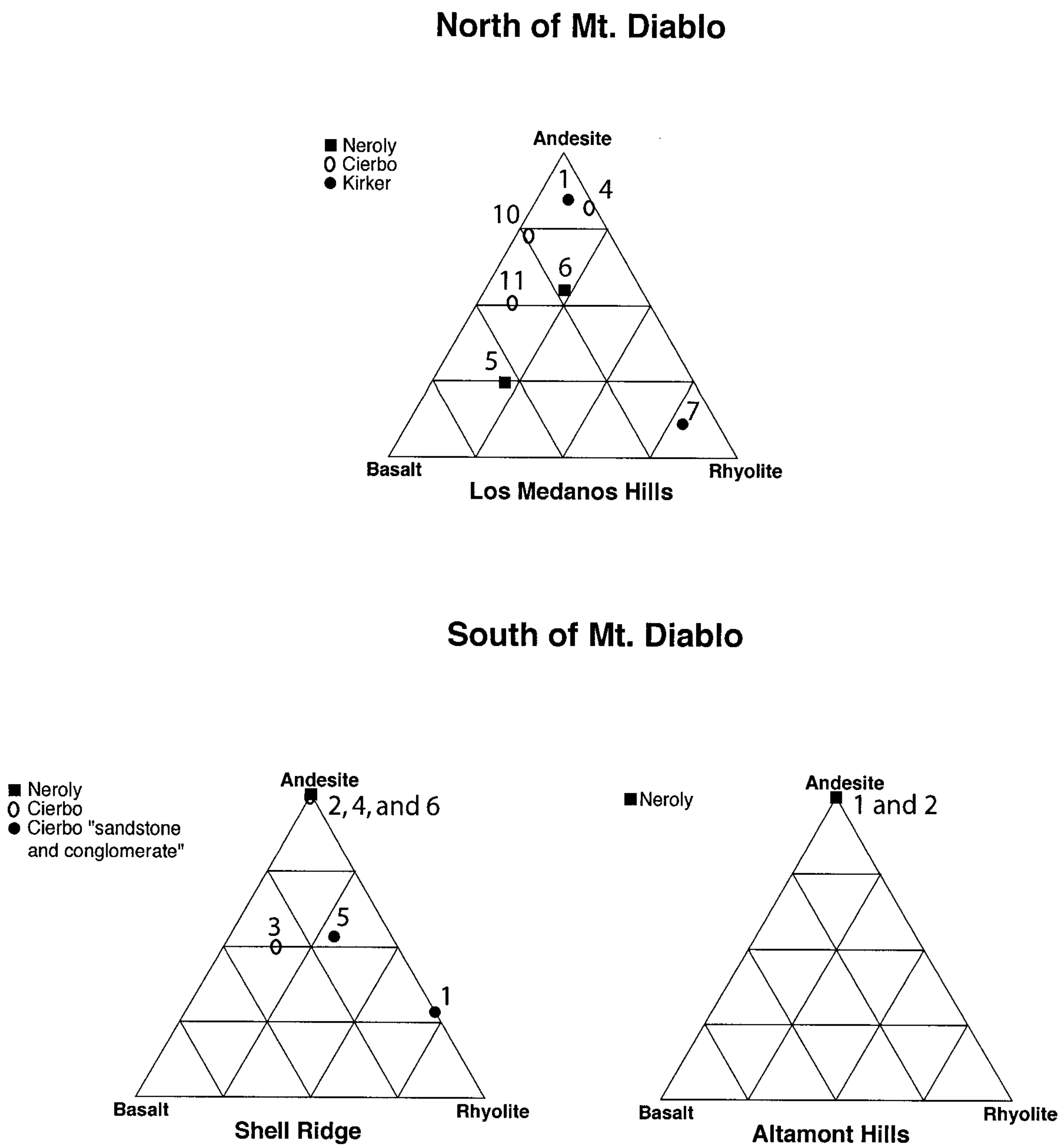

Figure 18. Ternary plots of volcanic clast populations at conglomerate count locations other than Happy Valley; numbers on plots refer to location numbers.

conglomerate," and Cierbo Sandstone are dominated by metamorphic clasts (Fig. 17) and are contained in feldspathic litharenite. Exceptions are LMH 1 in the Kirker Formation and SR 6 in the Cierbo Sandstone, where the volcanic populations are dominant. Units older than the Neroly tend to have mixed volcanic populations (Fig.18).

The Neroly conglomerate is dominated by volcanic clasts except at Happy Valley. The sandstone beds in the Neroly and the matrix of its conglomerates are composed of volcanic litharenite. Andesite is the most abundant volcanic rock type in most Neroly conglomerate outcrops; basalt is more abundant in the lower Neroly (LMH 5) at Kirker Creek.

Los Medanos Hills

Kirker Formation. The two counts done in this unit differ from each other in several key respects (Fig. 17). At LMH 7, the eastern location (Fig. 9), metamorphic clasts make up most of the population, with less abundant volcanic clasts. At LMH 1, the western location, volcanic clasts make up most of the population, with fewer metamorphic clasts. The percentage of metavolcanic clasts in the total metamorphic population is 44% at LMH 7 and 23% at LMH 1. The volcanic subpopulations at both LMH 1 and LMH 7 are heterogeneous (Fig. 18), but LMH 7 is dominated by biotite-quartz-rhyolite clasts, whereas LMH 1 is dominated by andesite clasts. Sphericity and roundness are low for the metamorphic clasts and comparatively high for the volcanic clasts.

Cierbo Sandstone. All three Cierbo conglomerate samples are dominated by metamorphic clasts, and volcanic clasts are less abundant (Fig. 17). The percentage of metavolcanic clasts in the total metamorphic population ranges from 25% to 35%. The volcanic populations are also similar to each other (Fig. 18); all three locations are mixed, and andesitic clasts are the most common. The rhyolitic clasts include both rocks bearing biotite and quartz and rocks bearing only quartz.

Neroly Sandstone. The Neroly is dominated by volcanic clasts at both LMH 5 and LMH 6. The rest of the population at both locations is composed mostly of metamorphic clasts (Table 2). The volcanic population at both locations is mixed (Fig. 18). At LMH 5, very dark, aphanitic basalt clasts are the dominant type and andesite clasts are the next most common, whereas at LMH 6 andesite clasts are the most abundant type and rhyolite clasts are the next most common (Fig. 18). Rhyolite clasts, which make up about 20% of the volcanic population, include biotite-quartz rhyolite and quartz rhyolite. LMH 5 is the only Neroly location studied where the volcanic population is not dominated by andesite clasts (Fig. 18).

Not included in the count data but observed in the field are cobble- to boulder-size basalt clasts. These clasts were noted at several different horizons in the lower portion of the Neroly in the Kirker Canyon area.

Shell Ridge

Cierbo "Sandstone and Conglomerate." Two clast counts, SR 1 and SR 5, were done in the basal conglomerate (Fig. 12). Both locations have high percentages of metamorphic clasts (Fig. 17). The percentage of metavolcanic clasts in the total metamorphic population is 65% at SR 1 and 27% at SR 5. Volcanic clasts make up a small percentage in the two locations. The volcanic subpopulations in both locations are mixed, although only location SR 5 has any basalt clasts (Fig. 18). Rhyolite clasts are of two types, biotite-quartz rhyolite and quartz rhyolite. Porcellanite clasts were noted in this unit, the only case where this clast type was noted.

Cierbo Sandstone. Two clast counts were done in this unit. Site SR 3 is in a lower, shell-rich conglomerate. The second, SR 6, is in a conglomerate near the top of the formation (Fig. 12). SR 3 is dominated by metamorphic clasts (Fig. 17), about 50% of which are metavolcanic clasts. The volcanic population is heterogeneous, with andesite, basalt, and rhyolite clasts (Fig. 18). The rhyolite clasts include those that contain biotite and quartz and those that contain only quartz phenocrysts.

The upper conglomerate, SR 6, is composed mostly of volcanic clasts (Fig. 17). The volcanic subpopulation is 99% andesite clasts and 1% basalt clasts (Fig. 18). The metamorphic population is 38% metavolcanic clasts.

Neroly Sandstone. Two clast counts (SR 2 and 4) were done in the Neroly Sandstone. Both counts show that volcanic clasts are predominant (Fig. 17). SR 4 is almost entirely composed of volcanic clasts (98%), all of which are andesite. The percentage of metavolcanic clasts in the metamorphic population is 25% (of a total of 8 metamorphic clasts). SR 2 has a smaller percentage of volcanic clasts (64%) but, like SR 4, has a volcanic subpopulation composed entirely of andesite clasts (Fig. 18). The remaining clasts are about 25% metamorphic and 10% black chert and vein quartz (Table 2). The metavolcanic clasts are 31% of the metamorphic population.

Altamont Hills

Both Altamont Hills clast counts were done in the same clast-supported conglomerate in the middle of the Neroly. The locations are within 2 km of each other (Fig. 13). The composition is dominated (90%) by volcanic clasts (Table 2 and Fig. 17). Next most abundant are metamorphic clasts (Table 2 and Fig. 17). In the volcanic subpopulation all the clasts are andesite (Fig. 18). The percentages of metavolcanic clasts in the total metamorphic population at the two locations are 7% and 8%.

Happy Valley

The conglomerate here is very different from that at any of the other Neroly count locations. The percentage of metamorphic clasts (84%) is higher than in any unit at any other location in the study area (Fig. 17). Of the total metamorphic clasts, 11% are metavolcanic. There are no volcanic clasts at this location, even though the enclosing sandstone is volcanolithic in composition.

The metamorphic subpopulation is composed of 40% graywacke, 30% blueschist, 17% unidentified metamorphic, 11% metavolcanic, and 2% serpentinite and metasedimentary clasts other than graywacke.

Paleocurrent Data

Paleocurrent data were collected in the Neroly Sandstone at three different sites. The data are presented in Table 3 and the results are shown in Figure 19. Paleocurrent data in the Los Medanos Hills were collected from large trough cross-beds. Twenty-nine measurements yielded a mean direction of 190 degrees (S 10 W). On Shell Ridge, paleocurrent data from eight trough cross-beds in the lower

TABLE 3. PALEOCURRENT DATA FOR THE NEROLY SANDSTONE

LOS MEDANOS HILLs (near Kirker Creek)

	Individual measurements: Azimuth (degrees)	Vector resultant: Resultant direction	Vector resultant: Vector strength
LMH 3		161.62	0.4871
	93		
	154		
	170		
	275		
LMH 13		184.16	0.6204
	281		
	193		
	180		
	190		
	129		
	269		
	132		
	150		
LMH 12		285.43	0.8978
	269		
	257		
	303		
	329		
	272		
LMH 6 east		160.45	0.2362
	70		
	95		
	86		
	230		
	248		
	230		
LMH 6 west		160.61	0.7944
	200		
	133		
	130		
	219		
	118		
	170		
All LMH		190.00	0.4004

SHELL RIDGE

	Individual measurements: Azimuth (degrees)	Vector resultant: Resultant direction	Vector resultant: Vector strength
SR 4		227.48	0.9795
	230		
	225		
	240		
	226		
	228		
	200		
	230		
	240		

ALTAMONT HILLS

	Individual measurements: Azimuth (degrees)	Vector resultant: Resultant direction	Vector resultant: Vector strength
AH 1			
*	320	320	1.00
AH 2			
*	10		
*	320		
*	300		
*	10		
#	290	335.7	0.88
All AH		327.72	0.8563

* arithmetic mean for 20 clast imbrications.
\# single cross-bed

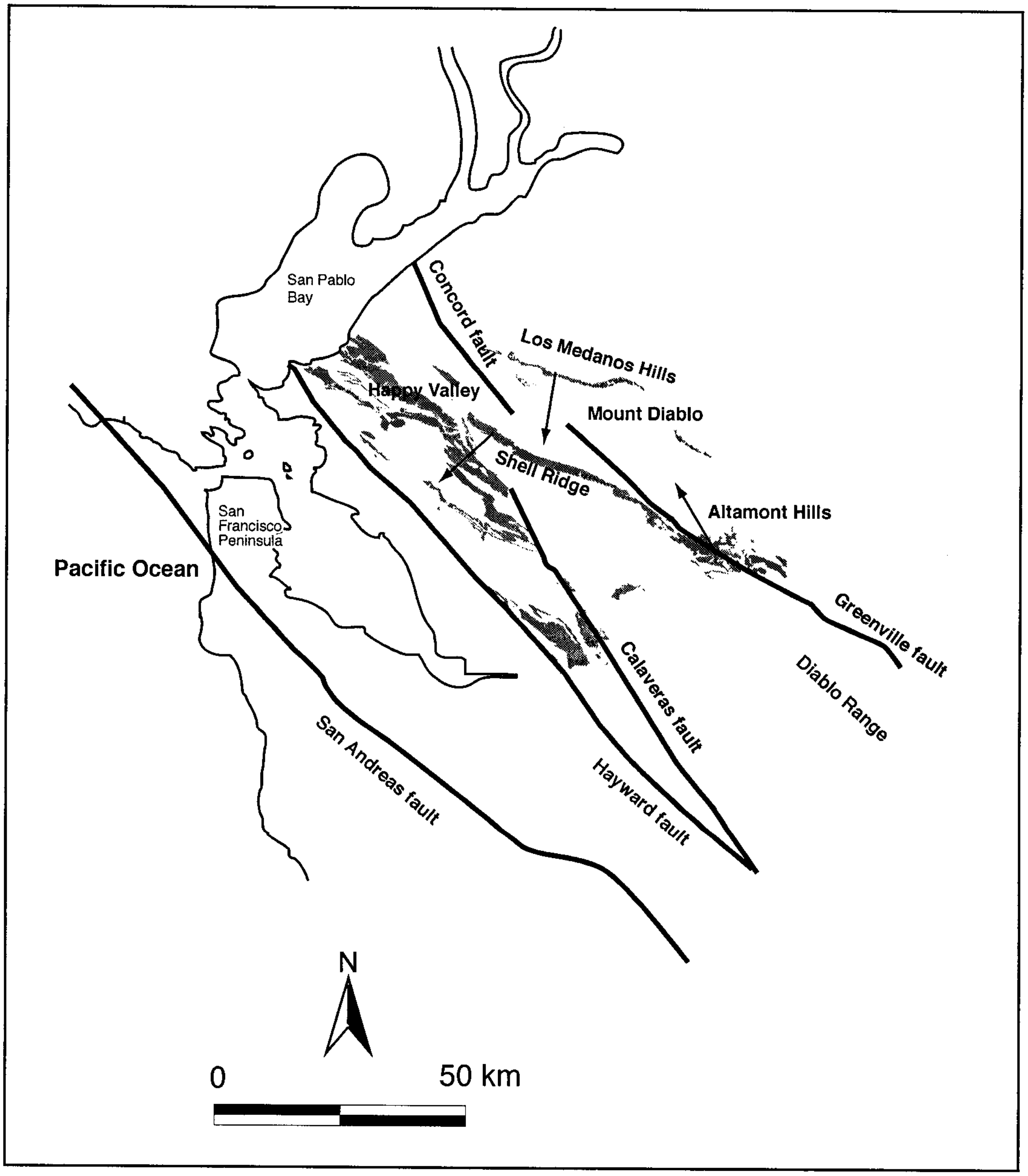

Figure 19. Map showing paleocurrent directions in the Neroly Formation. Altamont Hills data are from imbrication and one set of cross trough beds. The outcrop pattern of the the Kirker Formation and San Pablo Group is shown in gray.

section of the Neroly give an average of 227 degrees (S 47 W). In the Altamont Hills, paleocurrent data in the Neroly are from 5 clast imbrication sets (20 clasts each) and from 1 trough cross-bed in the conglomerate bed. The average for all Altamont Hills measurements is 328 degrees (N 32 W).

INTERPRETATION

Provenance

The most abundant clasts are volcanic and metamorphic rocks. In general, metamorphic clasts are most numerous in the lower units and appear to be derived from both the Sierra Nevada and the Coast Ranges. In the Neroly Sandstone, volcanic clasts generally dominate (Fig. 17). Volcanic clasts appear to have been derived from the northern and central portions of the Sierra Nevada.

Volcanic Population

All volcanic clasts are inferred to be of Sierran provenance, based on their petrologic characteristics, the known ages of the possible volcanic sources, and the age constraints of the sample outcrops.

Andesite is the most common clast type. Andesitic clasts from the count locations contain pyroxene, hornblende, and feldspar. Many also have a red groundmass, similar to some of the rocks encountered in the Sierra Nevada. All the andesitic rocks in the Sierra and at the count locations lack biotite. The Quien Sabe Volcanics (Drinkwater, 1983), the only other andesitic rocks of relevant age, do contain biotite. Because of the similarity between the andesites of the different Sierran formations, it is not possible to correlate any of the andesitic clasts studied to a specific source area within the Sierra Nevada.

Basalt clasts are correlated to the Lovejoy Formation, found in the northern Sierra Nevada and other localities north of the study area. This correlation is based on the comparatively dark color and on the aphanitic groundmass texture of these basaltic rocks. Basalts of similar age in the Berkeley Hills Volcanics are much lighter gray than the Lovejoy Basalt and the basalt clasts found in the study area.

The rhyolitic clasts appear to be of two types: those that contain biotite and quartz phenocrysts, and those that contain only quartz phenocrysts. The biotite-quartz rhyolite correlates with the Delleker Formation in the northern Sierra Nevada. The quartz rhyolite correlates with either the Valley Springs Formation or the Hartford Hills Rhyolite.

Northern and Central Sierran Volcanic Subpopulations

The northern subpopulation can be distinguished by the presence of basalt clasts from the Lovejoy and its related formations; the presence of rhyolite clasts that contain biotite, indicating the Delleker Formation; or both. The central volcanic provenance is defined by the lack of basalt and biotite-bearing rhyolite clasts. The central volcanic area is composed mostly of andesite with or without a small amount of quartz rhyolite.

The presence of biotite-quartz-rhyolite clasts convincingly points to a source in the Delleker Formation and a northern source. In contrast, the occurrence of quartz-rhyolite clasts could indicate a source in the Valley Springs Formation or the Hartford Hills Rhyolite and a central Sierran provenance, or these could be small clasts from the Delleker that do not contain biotite. For this reason, a lack of basalt clasts is a far more reliable indicator of a central Sierran provenance than the lack of biotite-bearing rhyolite.

The volcanic subpopulation in the Kirker Formation at LMH, the Cierbo "sandstone and conglomerate" at SR, and the Cierbo Sandstone on both sides of Mount Diablo shows a northern or mixed provenance based on the presence of Lovejoy basalt clasts and biotite-bearing Delleker clasts. Outcrops of Neroly Sandstone north of Mount Diablo containing both basalt and biotite-quartz rhyolite show a similar northern Sierran provenance. In contrast, the Neroly at locations to the south of Mount Diablo lacks basalt clasts. These locations contain only andesite clasts, and reflect a central Sierran provenance.

Coast Range Sources

The clast counts in the Neroly at Happy Valley show no volcanic clasts. The metamorphic population at Happy Valley is composed mostly of metagraywacke and blueschist clasts. Based on this metamorphic assemblage, the conglomerate is inferred to have been derived from the Coast Ranges (Graham et al., 1984). In the Altamont Hills, where 90% of the population is derived from Sierran volcanic rocks, the metamorphic population is composed of metagraywacke, blueschist, and serpentinite, showing that the Altamont Hills also have a Coast Range component to their provenance.

Proportions of Volcanic and Metamorphic Clasts

The volcanic and metamorphic clast distributions are important because these clasts can have different transport histories. In general, the Sierra Nevada has a greater proportion of metavolcanic rocks than the Coast Ranges (Jennings et al., 1977). In the Coast Ranges, most of the rocks are from non-metavolcanic types of metamorphic rocks, especially graywacke. Metavolcanic and metamorphic clasts transported from the Sierra could have commingled with proximally derived Coast Range clasts. It is predicted that, as the percentage of Coast Range-derived clasts increases in a sample population, the proportion of metavolcanic clasts within the metamorphic population should decrease.

Happy Valley lies on the western edge of the embayment in which the San

Pablo Group was deposited. The conglomerate outcrop at this location contains no volcanic clasts (Fig. 17), even though it is contained in a volcanolithic sandstone that is clearly the Neroly. The high percentage of graywacke and blueschist clasts, the lack of volcanic clasts, and the angularity of clasts suggest that its coarse clasts were derived entirely from the nearby Coast Ranges to the west. The total metamorphic population in the Neroly at Happy Valley contains about 10% metavolcanic clasts. This can be considered a baseline representative of the Coast Range provenance in this area.

Happy Valley (HV 1) represents a single provenance; the clasts were derived from the Coast Ranges. The Altamont Hills sites (AH 1 and 2) have volcanic clasts derived from Sierran rocks, but the metamorphic clasts are derived from Coast Range rocks.

Figure 20 is a plot of the metavolcanic clasts against total metamorphic clasts. All of the Neroly locations except HV 1 (which lies on the opposite side of the basin) plot in the lower left portion of the field. In addition, Kirker LMH 1 and Cierbo SR 6, which have large volcanic populations like the Neroly locations, also have less than 30% metamorphic clasts and group with the Neroly samples. The units older than the Neroly show an abrupt increase in total metamorphic clasts where the metavolcanic population reaches approximately 15%. This increase may be due to the fact that Sierran metamorphic sources had not yet been covered by volcanic deposits. The trend lines on Figure 20 show two possible demarcations for the Coast Range and Sierran provenances found in this study. The points to the left of the 20% line evidently have metamorphic populations derived form the Coast Ranges, points to the right of the 45% line have metamorphic populations from the Sierra Nevada,

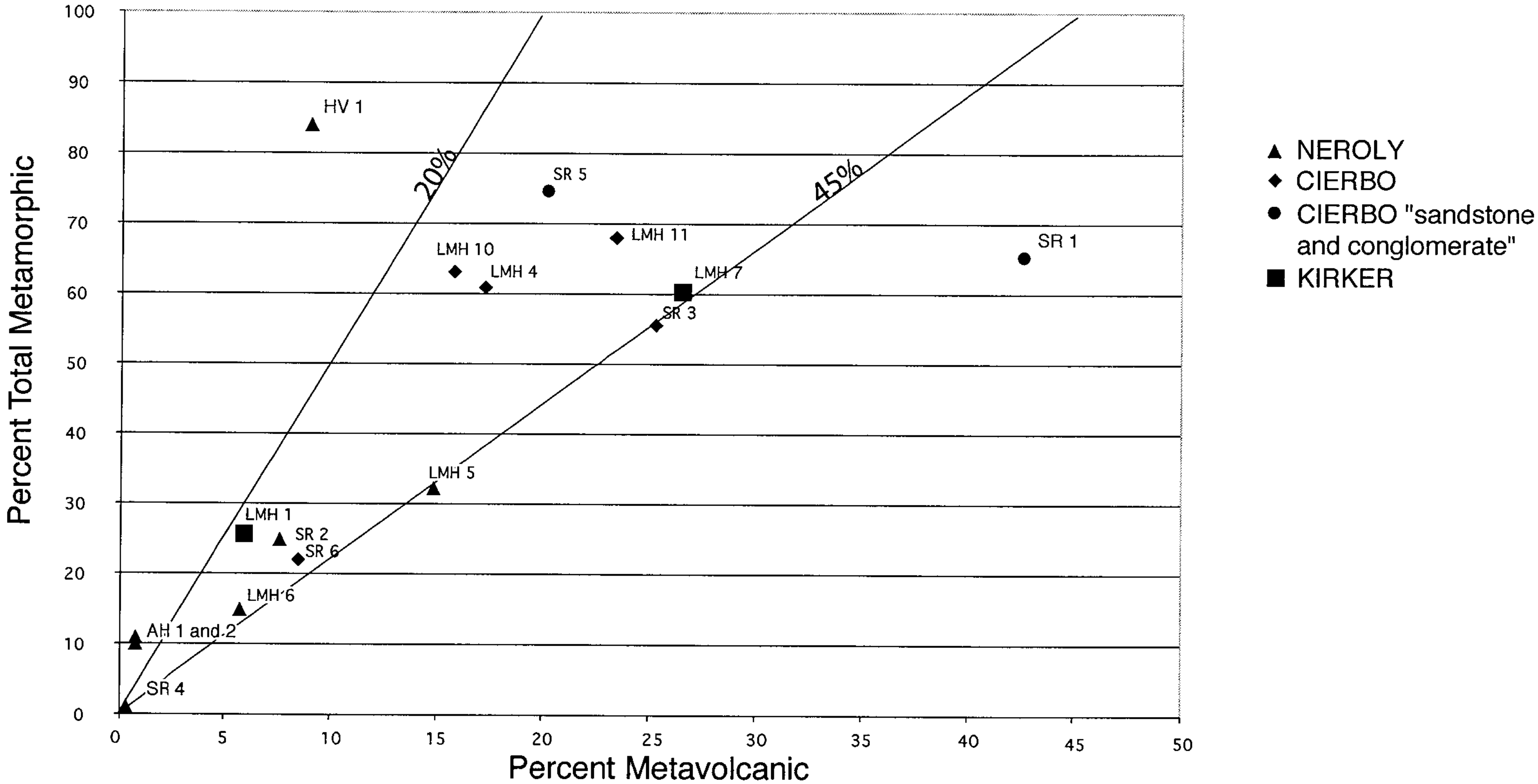

Figure 20. Percentage of metavolcanic clasts plotted vs. the percentage of total metamorphic clasts. Lines show metavolcanic clasts as 20% and 45% of the total metamorphic population.

and points between the two lines are inferred to have a mixed provenance.

Figure 21 is a plot of the percentage of metavolcanic clasts in the total metamorphic population (metavolcanics/ metavolcanics + “other metamorphics”) against the percentage of volcanic clasts at each location. The locations with more than 80% volcanic clasts had sources in fluvial systems in the Sierra Nevada that were inundated with volcanic material (Curtis, 1954), so no other clast types were available for transport from the Sierran source terrain. In contrast, rocks at the count locations with fewer volcanic clasts probably were deposited when the Sierran source terranes were not entirely inundated with volcanic rocks, and had a more heterogeneous population available for transport.

While it is not possible from this study to assign a Sierran provenance end-member to the metamorphic population, SR 1 appears to be closest to such an end-member for this limited data set. LMH 5 is the end-member for the Neroly samples. LMH 5 also has the smallest volcanic population for a Neroly location (again ignoring HV 1), suggesting that the Sierran system that carried the volcanic clasts was not totally inundated with volcanic rocks and so had metamorphic clasts available for transport. Based on the above observations, locations with 20-45% metavolcanic clasts have metamorphic populations that suggest a mixed Sierran/Coast Range provenance in the metamorphic populations

Relationships of Conglomerate to Enclosing Sandstone Matrix

The composition of conglomerate beds studied here parallels the composition of the enclosing sandstone. The Kirker Formation, the Cierbo “sandstone and

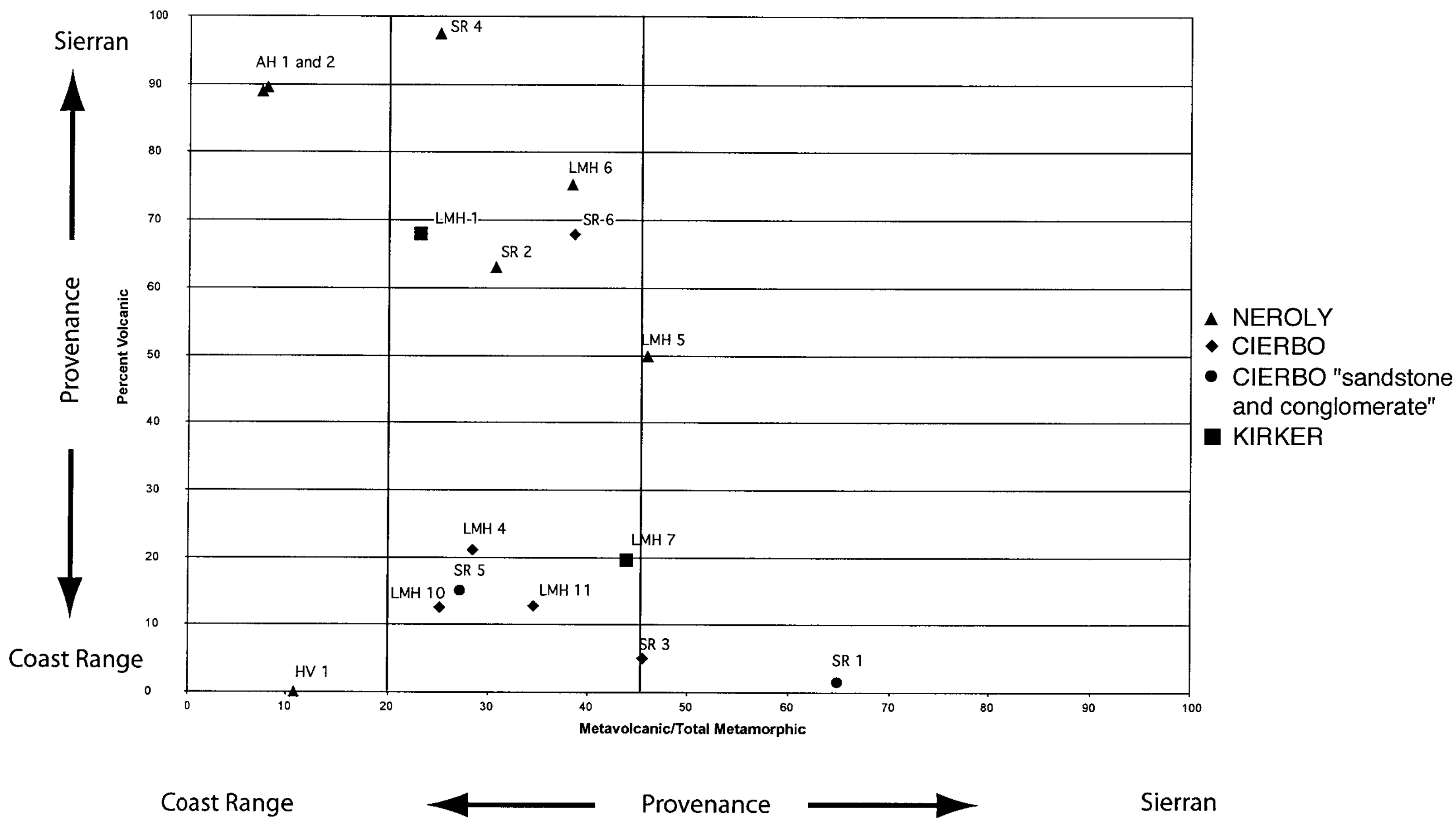

Figure 21. Percentage of volcanic clasts plotted vs. percentage of metavolcanic clasts in the total metamorphic clast population and the assumed trend for the provenance end-members based on the separate subpopulations. See text for explanation of assumed provenance. Vertical lines mark the metavolcanic clasts as 20% and 45% of the total metamorphic clasts population; these lines are also plotted on Figure 20.

conglomerate," and the Cierbo Sandstone tend to have conglomerate beds dominated by metamorphic clasts contained in feldspathic litharenite. Most of the volcanic clast-dominated Neroly conglomerates are interbedded with volcanolithic litharenite. The Cierbo location (SR 6) that contains more than 50% volcanic clasts is located just below the contact with the overlying Neroly. Like the Neroly locations, the volcanic population in SR 6 is dominated by andesite clasts, suggesting a gradational relationship between the two units.

The one exception to the relationship outlined above is the Happy Valley location, where the conglomerate is dominated by metamorphic clasts to the total exclusion of volcanic clasts, but is contained in a volcanolithic litharenite. This difference at HV 1 is due to its position on the opposite (western) side of the depositional basin from the Sierra Nevada river systems sourced to the east, where it only received locally derived gravel from the west.

Changes through Time

Two major changes are recorded in the history of the rocks studied. The first and most obvious change is from a metamorphic-dominated assemblage in the Kirker, Cierbo "sandstone and conglomerate," and Cierbo Sandstone to a volcanic-dominated assemblage in the Neroly. The second change is the introduction of a second petrofacies. The provenance in the lower units appears to be the same throughout the area studied, whereas the Neroly north of Mount Diablo has a different provenance than it does to the south. The northern Neroly has a northern Sierran provenance and the southern Neroly has a central Sierran provenance.

Sediment Dispersal

In the Los Medanos Hills, the Kirker Formation and Cierbo Sandstone range from continental in the southeast to marine in the northwest (Sullivan et al., 1995b). In the fluvial section of the Neroly near Kirker Creek, paleocurrent directions show transport directions from the north-northeast. In the Shell Ridge area, the fluvial portions of the Neroly show transport from the northeast. In the fluvial Neroly in the Altamont Hills, the paleocurrent data and metamorphic clast provenance indicate transport from the southeast, but the volcanic clasts clearly are derived from the Sierra Nevada to the east. The composition of the conglomerate in the Neroly Sandstone at Happy Valley indicates that sediment was derived from the west.

Paleoenvironment

The interpretation of paleoenvironments is based mostly on field observations undertaken during this study. The observations and their interpretations are contained in Appendix A.

The Kirker Formation is fluvial. The Cierbo "sandstone and conglomerate" is coastal marine at SR 1 and probably marine (or possibly fluvial) at SR 5. All of the Cierbo Sandstone locations are marginal marine or estuarine with the exception of LMH 10 at the southeastern end of the Los Medanos Hills, which is fluvial. Within the Neroly in the Los Medanos Hills, LMH 6 is fluvial and LMH 5 is marine. In the Shell Ridge section the Neroly is marine at SR 2. In the Neroly at SR 4 the conglomerate is in the base of a subaqueous debris flow contained in marine sandstone, but abundant leaf fossils in the debris flow suggest that the source of the conglomerate is continental. Both Altamont Hills locations are fluvial. Within each of the units studied, the composition at different locations appears to be the same regardless of the environment of deposition, suggesting that environment of deposition did not affect the composition of the sediment.

DISCUSSION

Age of the Kirker Formation

Previous workers (e.g., Primmer, 1960) have suggested that the Kirker Formation is Oligocene, but this age cannot be reconciled with the volcanic assemblage within the Kirker Formation. Oligocene volcanic rocks in the Sierra Nevada are primarily or exclusively rhyolitic (Figs. 4, 5), but the volcanic clast subpopulation of the Kirker Formation is heterogeneous at location LMH 7, where it is mostly rhyolite with lesser amounts of andesite and basalt, and primarily andesitic at LMH 1 (Fig 18). If the andesite in the conglomerates is Sierran, it can be no older than 19.8 Ma (Fig. 4). This supports the suggestion of Sullivan et al. (1995b) that the Kirker is Miocene in age.

The Kirker Tuff, which overlies the basal conglomerate bed where the counts took place, is not correlated to any known tephra unit. But it has a chemical affinity with rhyolite of the Valley Springs Formation (A. Sarna, personal commun., 2001). The youngest Miocene date on a Sierran rhyolite is 16.5 Ma (Fig. 5). The Kirker Tuff and the conglomerate at the base of the Kirker Formation are therefore most likely to be between 16.5 Ma and 19.8 Ma. The presence of a small number of basalt clasts at the base of the Kirker Formation suggests that it may be no older than the 16 Ma Lovejoy Basalt.

The Kirker Formation may be correlative with the Cierbo "sandstone and conglomerate" on the southwest flank of Mount Diablo. The Kirker Formation and the Cierbo "sandstone and conglomerate" are the oldest Tertiary units studied here. The Cierbo "sandstone and conglomerate" contains microfuana giving an age of approximately 16 Ma (White, 1990). The age range for *Striostrea subtitan*, found several meters above the base of the Cierbo "sandstone and conglomerate," is

Oligocene to mid-Miocene (C. Powell, written commun., 2002). Both units rest unconformably on rocks of Eocene age, and three of the four Kirker and Cierbo "sandstone and conglomerate" locations have mixed volcanic populations.

Paleogeography

The basin in which the San Pablo Group was deposited appears to have been bounded on the west by the Hayward fault (Graham et al., 1984, Graymer et al., 2002). On the east side of the basin, the Neroly and Cierbo thicken from the east side to the west side of Mount Diablo. Mount Diablo is an anticline that is thought to be formed by the transfer of slip from the Greenville fault to the Concord fault (Unruh and Sawyer, 1997). These faults may be the structural boundary of the east side of the basin.

In the palinspastic reconstructions described below, regional shortening of about 10% was estimated by maintaining the orientation of the fault blocks when their relative positions were restored to the time of interest.

Kirker Formation and Cierbo "Sandstone and Conglomerate"

Based on the paleoenvironmental interpretations for the four Kirker and Cierbo "sandstone and conglomerate" locations (App. A), the paleogeography at this time, about 20-15 Ma, is inferred to include an eastern fluvial environment related to the Valley Springs Formation, with a source in the Sierra Nevada grading westward into a near-shore marine environment near the present location of the Los Medanos Hills. The presence of metamorphic and volcanic clasts at these locations indicates that the Kirker and Cierbo "sandstone and conglomerate" were receiving the majority of the clastic material from a dissected arc that was being reactivated (Dickinson and

Suczek, 1979) and receiving a small amount of material from the Coast Ranges to the north, south, or both.

Cierbo Sandstone

The conglomerates in the Cierbo Sandstone are very similar to each other, with the exception SR 6. The metamorphic population suggests a mixed Sierran and Coast Range provenance (Fig. 20). The volcanic population points to either a northern Sierran or a mixed, northern and central Sierran provenance (Fig. 18).

The sandstone units in most of the Cierbo Sandstone locations are feldspathic litharenites. The exception to this is the sandstone mapped as Cierbo Sandstone in the Altamont Hills, which is quartzofeldspathic, suggesting a different provenance for the Cierbo in the Altamont Hills. The source of the sandstone there probably is the Sierra Nevada south of the Merced drainage (Walker, 1996).

The upper and lower contacts of the Cierbo at the southeastern end of the Los Medanos Hills are erosional (R. Sullivan, personal commun., 2002). The Cierbo Sandstone thins to the southeast, so that it is not present in the southeastern tip of the Los Medanos Hills, but it does crop out in the Altamont Hills, where it has a southern Sierran provenance. This suggests that the Cierbo was deposited in an embayment similar to that suggested by Buising and Walker (1995) but with a developing high south of Los Medanos Hills (Fig. 22) and northeast of modern Mount Diablo. The embayment received detritus from two separate drainage systems from the Sierra Nevada (Fig. 16), one from the northern Sierran volcanic source area and a second from the southern Sierran crystalline basement source area (Walker, 1996).

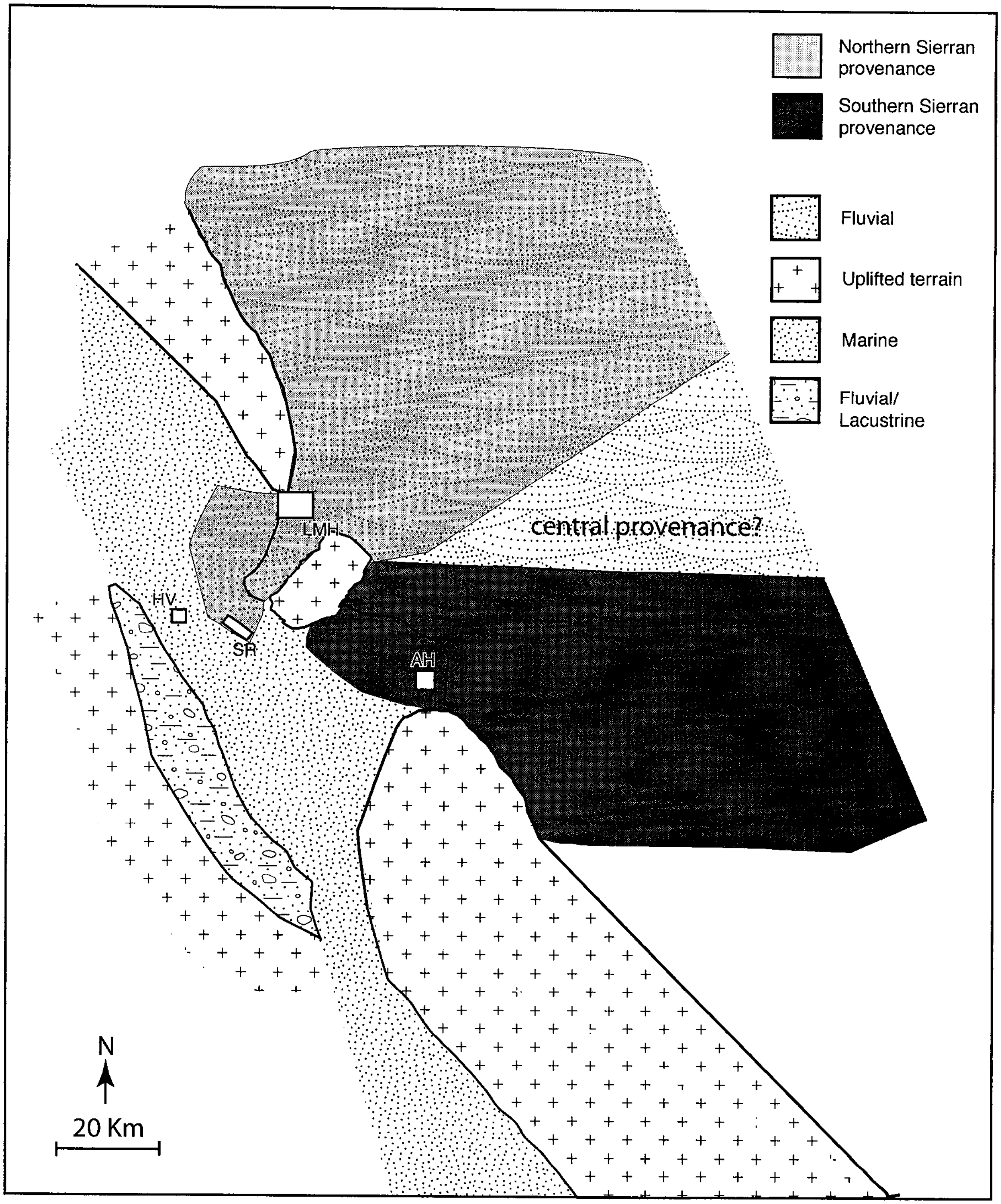

Figure 22. Palinspastic paleogeographic reconstruction of the east Bay area circa 12 Ma. Northern Sierran provenance shown in light gray, southern Sierran provenance shown in dark gray. Study areas are shown for location reference (LMH,Los Medanos Hills; SR, Shell Ridge; HV, Happy Valley; AH, Altamont Hills).

Neroly Sandstone

Los Medanos Hills. On the northeast flank of Mount Diablo, the mixed volcanic clast population is similar to that of the underlying units. The mixed volcanic population and the presence of basalt clasts in the Neroly on the north flank of Mount Diablo indicate at least a partly northern Sierran provenance.

The cobble- to boulder-size clasts of basalt in the Neroly Sandstone near Keller Canyon make the Putnam Peak Basalt (Fig. 3) a particularly appealing candidate for their source. Most of the smaller basalt clasts could have originated in the Sierra or other more distant locations. In addition, paleocurrent data collected in the Keller Canyon area suggest a paleocurrent direction from the north-northeast (Table 3). The paleocurrent data are derived from large, low-angle cross beds, suggesting a large fluvial system. An additional observation supporting the idea that the basalt clasts came from the Putnam Peak locality is that the contact between the Neroly Sandstone and the underlying Putnam Peak Basalt at Putnam Peak is an angular unconformity (Siegel, 1988).

The presence in the Neroly of large basalt clasts, most likely derived from the Putnam Peak Basalt, suggests that the Neroly also has a Northern Coast Range component to its provenance. Neroly on the north flank of Mount Diablo was deposited by rivers that flowed from the northern half of the Sierra across the Central Valley, were deflected to the south by an emergent northern Coast Range, and then flowed to the west into an embayment that is recorded by the San Pablo Group (Fig. 23). This is a pattern similar to that of the modern Sacramento River, and it remained unchanged during the deposition of the Cierbo and Neroly sandstones.

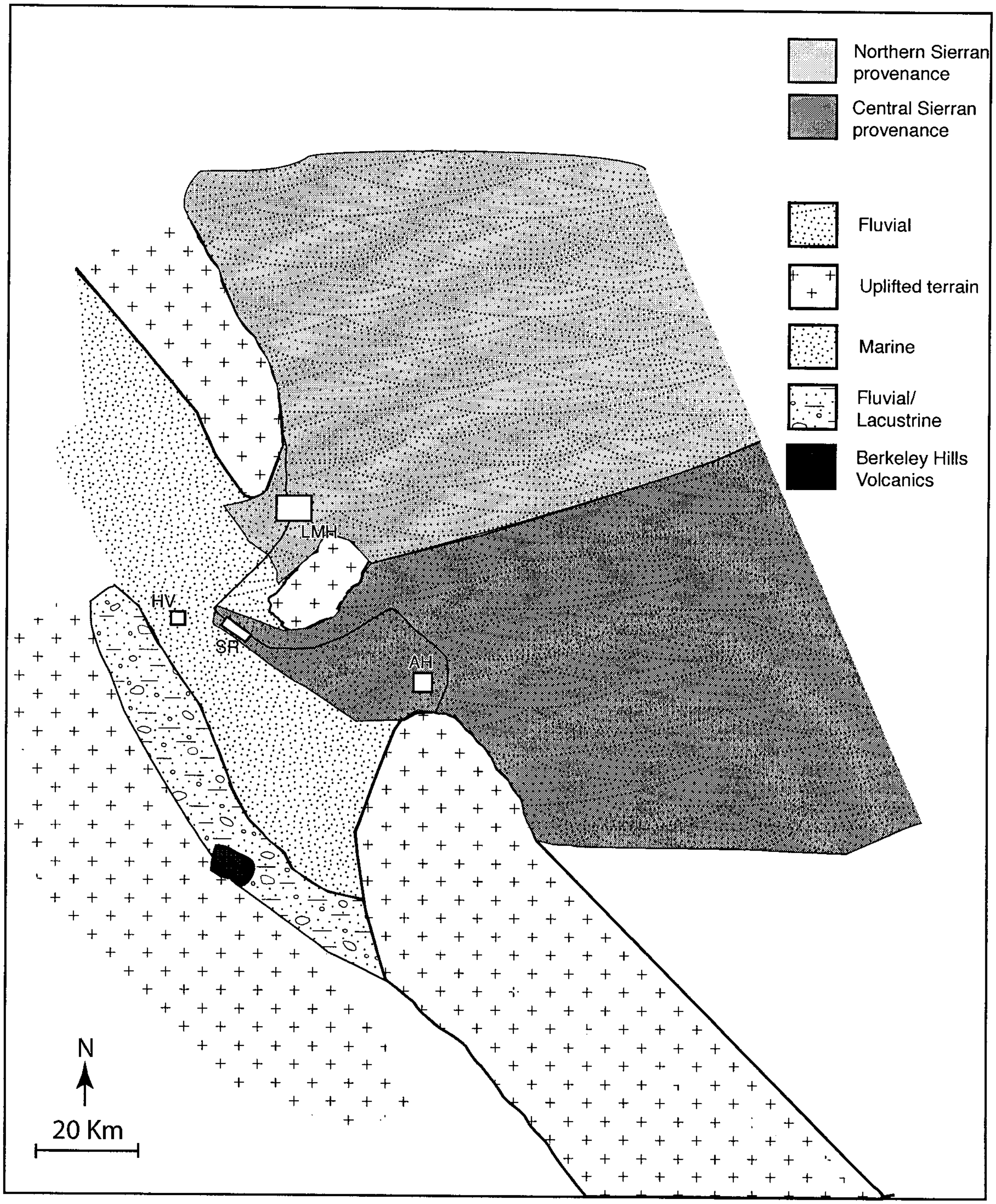

Figure 23. Palinspastic paleogeographic reconstruction of the east Bay area circa 10 Ma. Northern Sierran provenance shown in light gray, central Sierran provenance shown in dark gray. Study areas are shown for location reference (LMH, Los Medanos Hills; SR, Shell Ridge; HV, Happy Valley; AH, Altamont Hills).

Shell Ridge and Altamont Hills. In contrast to the Los Medanos Hills, the Neroly at Shell Ridge and in the Altamont Hills, both located south of Mount Diablo, has volcanic populations with only a central Sierran provenance. SR 2 has a slightly lower percentage of volcanic clasts than at AH 1 and AH 2. SR 2 is a nearshore marine deposit, and its mixed Coast Range and Sierran provenance may be due to longshore drift from the area of AH 1 and AH 2.

In the Altamont Hills, paleocurrent data show flow to the northwest (Fig. 19). Consistent with the paleocurrent data is the occurrence of a Coast Range population of metamorphic clasts in the conglomerates, suggesting that streams drained the Sierra Nevada, flowed across the Central Valley, and were then deflected to the north by the nascent Coast Range (Fig. 23). This is comparable to the modern San Joaquin drainage system.

It appears from the discussion above that there were still two separate drainage systems from the Sierra during the deposition of the Neroly. The northern drainage system remained unchanged during the deposition of the Cierbo and Neroly sandstones. The southern fluvial system had a different provenance (central Sierran) during Neroly deposition than during the deposition of the Cierbo (from the Sierra south of the Merced drainage). The Neroly at Shell Ridge and the Altamont Hills is derived from the central Sierra between Donner Pass and the Merced River (Fig. 16).

Happy Valley. The source of the clasts in the conglomerate at Happy Valley is from the Coast Range, most likely from the Bay Block to the west (Graham et al., 1984). The sand-size fraction is composed of volcanolithic grains evidently of Sierran origin. The contrast in sources is most likely due to relative transport energies necessary for the entrainment of the different size fractions of the sandstone and conglomerate.

The lack of volcanic clasts in the Neroly conglomerate at Happy Valley has implications for its relationship with the fluvial and lacustrine Contra Costa Group and the Berkeley Hills Volcanics (Fig. 23). The Contra Costa Group interfingers with the Neroly, at least to the south (Buising and Walker, 1995); the relation between the two units to the north at the latitude of Happy Valley is not known. Dickerman (1999) found a significant percentage of volcanic clasts in the Contra Costa Group conglomerates. The Berkeley Hills Volcanics interfinger with the Contra Costa Group and are the source for the volcanic clasts in it. The Berkeley Hills Volcanics were erupted between 9.99 and 9.2 Ma (Grimsich et al., 1996).

The lack of volcanic clasts in the Neroly at Happy Valley can be explained in two different ways. First, the Neroly may be slightly too old to contain material derived from the Berkeley Hills Volcanics. The best age controls for the Neroly are to the east in the Los Medanos Hills, where tephra correlations suggest that the top of the Neroly is at least as young as 9.8 Ma, but the Neroly could be younger (Sarna and Walker, 1999). However, the age of the Neroly at Happy Valley is not well known, and the unit lacks tephra, so that correlation with sections to the east is not possible. The conglomerate counted at Happy Valley is near the top of the Neroly, and it is possible that the section at Happy Valley is older than the Berkeley Hill Volcanics.

Secondly, it is possible that the Neroly at HV 1 and the Berkeley Hills Volcanics were separated from each other in the Miocene by a greater distance than they are at present (Fig. 23). In this scenario the two sections are coeval and the lack of volcanic clasts at Happy Valley is due to fault offset. Graymer et al. (2002) have postulated that as much as 50 km of slip could have occurred between the

Calaveras and Hayward faults, on the Moraga-Miller Creek-Palomares fault system. If this is correct, the Berkeley Hills Volcanics would have been approximately 50 km south of Happy Valley during the time of eruption and possibly too far away to be a source of volcanic material. Unless the age of the top of the Neroly is older on the west side of the basin than on the east, the lack of volcanic clasts in the Neroly at Happy Valley suggests that the separation between the Neroly and the Berkeley Hills Volcanics and its associated sedimentary unit, the Contra Costa Group, was much greater than it is today.

Paleodrainage Divide

The nature of the paleodrainage divide that separated the northern and southern drainage systems during deposition of the Neroly and Cierbo is not clear. The drainage divide may have been controlled by the drainage pattern farther to the east in the Sierra Nevada and Central Valley, it may have had a more proximal control, or it may have been affected by both factors.

Evidence for a more proximal control is the erosional, unconformable nature of the upper and lower contacts of the Cierbo in the southeastern Los Medanos Hills. Farther southeast, where the Cierbo reappears and thickens to the southeast of Mount Diablo, it has a different provenance than in the Los Medanos Hills. Another piece of evidence is the presence of a subaqueous debris flow in the Neroly at Shell Ridge (SR 4), which requires relief to the east in the area presently occupied by Mount Diablo. Two sides of the area presently occupied by Mount Diablo thus show evidence of uplift, and the provenance on the north and south sides of the area is different. Together these observations imply a paleodrainage divide at the present location of Mount Diablo (Figs. 1, 22, and 23).

The pattern of uplift for the local paleohigh suggests that it propagated from east to west, consistent with the model for the growth of the Mount Diablo anticline proposed by Unruh and Sawyer (1997). If this is the case, then at least some strike-slip motion must have taken place at the latitude of Mount Diablo by the time the Cierbo was deposited.

CONCLUSIONS

The Miocene section studied in the east Bay area records an evolving depositional system. Most of the clastic material was derived from three distinct areas in the Sierra Nevada, but a secondary population, which locally is dominant, was derived from the Coast Ranges to the north, south, or west.

The stratigraphically lowest count localities, in the Kirker Formation and the Cierbo "sandstone and conglomerate," contain volcanic and metamorphic clasts inferred to have been derived mainly from the Sierra Nevada. Some locations contain a large number of volcanic clasts, but others contain very few. The locations composed mainly of metamorphic clasts show a ratio of metavolcanic clasts to total metamorphic clasts indicative of a Sierran provenance with a minor component of Coast Range-derived material. The presence of Sierran andesitic clasts shows that the Kirker Formation is not older than 20 Ma.

The Cierbo Sandstone locations, comprising the middle of each of the sections studied, mostly show a northern or mixed Sierran provenance composed of metamorphic clasts and volcanic clasts. The ratio of metavolcanic clasts to total metamorphic clasts in the Cierbo conglomerates is between 20% and 45%, most likely indicative of a component of metamorphic material derived from the Coast Ranges. No conglomerate outcrops were found in the Altamont Hills, but the character of the sand-sized fraction suggests that it was derived from the southern Sierra Nevada.

Based on the counts done in this study, the Neroly Sandstone is subdivided into regions showing three separate sources. The first region is in the Los Medanos Hills and contains both Lovejoy and Delleker clasts, indicating sources in the northern Sierra. The second region, near Shell Ridge and in the Altamont Hills, is composed dominantly of andesitic clasts typical of the Mehrten Formation, indicating a central Sierran volcanic provenance. The third region is represented by the site at Happy Valley, where the coarse clasts were derived from a Franciscan-rich Coast Range terrain, most likely the Bay Block. The Neroly metamorphic clasts evidently were chiefly derived from the Coast Ranges, based on the presence of metagraywacke and blueschist clasts, even where the volcanic populations show a Sierran provenance. Clasts from the Berkeley Hills Volcanics are absent from the Neroly conglomerates at Happy Valley, supporting the possibility of a large amount of slip on the Moraga-Miller Creek-Palomares fault(s).

The contrast between the northern and southern Sierran provenance of the Cierbo and the northern and central Sierran provenance of the Neroly (Fig. 16) points to the changes in the paleodrainage system east of the study area. The angular unconformities that mark all the contacts in the San Pablo Group in the eastern Los Medanos Hills, coupled with the presence of subaqueous debris flows in the Neroly at Shell Ridge, suggest the development of a local high near modern Mount Diablo.

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APPENDIX A: DESCRIPTION OF OUTCROPS

This appendix describes the stratigraphy and sedimentology of clast count locations.

Los Medanos Hills 1

The count location is in the Kirker Formation at the bottom of an unnamed drainage. The upper portions of the Kirker are composed of sandstone containing marine bivalves and *Astrodapsis*. The conglomerate where the count took place is at the base of the section. Due to the poor exposure, few bedding features were noted. The conglomerate is matrix supported and poorly sorted. Vertebrate fossils have been found in the conglomerate bed (R. Sullivan, personal commun., 1999).

The environment of deposition for the conglomerate is fluvial (Sullivan et al., 1995b). The overlying Kirker sandstone, based on the fossils, is coastal marine at this location.

Los Medanos Hills 4

This location in Kirker Creek is in the Cierbo of Graymer et al. (1994). It is a unique section approximately 2 to 4 m thick composed of lenses and stringers of conglomerate interfingering with cross-bedded sandstone and underlain by a 2- to 3-m-thick siltstone bed. Within the sandstone beds near the base of the conglomeratic interval are thin-shelled gastropods that are 1 to 2 cm long in beds with matrix material resembling the underlying siltstone. The underlying siltstone shows parallel to sub-parallel laminae. The siltstone contains horizontal, millimeter-scale burrows; there are also vertical, centimeter-scale burrows, some of which are filled with material from the overlying coarse unit. Fossilized wood was also found throughout the section. The color of the outcrop is brownish gray.

Based mainly on the presence of conglomerate and cross-bedded sandstone, this location is inferred to have been deposited in an open-coastal beach environment, probably upper shoreface. One sedimentary clast encountered at this location contained a pholad boring suggesting the presence of a nearby outcrop offshore.

Los Medanos Hills 5

This count locality is in the Neroly, stratigraphically above LMH 4 and overlying the cross-bedded tuff marker bed of Sullivan et al. (1995). The count was done in two matrix-supported conglomerate beds stratigraphically 1 m apart. The matrix, like the surrounding sandstone, is tuffaceous. The color of the outcrop is light bluish gray.

The regional extent of the cross-bedding at LMH 5 and its stratigraphic position relative to LMH 4 suggest that the environment of deposition for this location is coastal marine.

Los Medanos Hills 6

This location is approximately 75 m stratigraphically above LMH 5. This section is characterized by medium- to coarse-sandstone with large cross-bed sets that are 2 m wide and 0.5 m thick, the presence of iron oxide concretions, and rare conglomerate beds. Sorting is poor to very poor and the conglomerates are matrix supported. Outcrop color is brownish gray.

The Neroly at this location was deposited in a fluvial environment (Sullivan et al., 1995b).

Los Medanos Hills 7

This location is in the basal conglomerate of the Kirker Formation east of Markley Canyon (Fig. 11). The count took place in an exposure at the toe of a rotational slump. The clasts in the outcrop are matrix supported.

The environment of deposition for the conglomerate bed is inferred to be fluvial as at LMH 1 (Sullivan et al., 1995b).

Los Medanos Hills 10

Located near the crest of the ridge to the east of hill 989, this site is located in the Cierbo of Graymer et al. (1994). This location is composed of cross-bedded sandstone and conglomerate beds 0.5-1 m thick. The exposure contains 4 conglomerate beds separated by sandstone beds. The upper sandstone beds appear to be composed of clean, quartzose sand that is brownish gray on weathered surfaces and medium-light gray on unweathered surfaces. The grains of the lower beds have a pale-brown clay coating on weathered surfaces; on fresh surfaces the color is light bluish gray, suggesting that the clay is montmorillonite. The lower bed appears to be composed of quartz and volcanic (andesitic?) grains. The clasts are grain supported and moderately to well sorted.

The lack of marine fossils and the bedding styles described above suggest that the environment of deposition is probably fluvial at this location.

Los Medanos Hills 11

This location is along the fire road on the east flank of hill 989, stratigraphically above LMH 10, and is located in the Cierbo Sandstone. Approximately 13.5 m above the count location is a shell hash composed entirely of *Striostrea ? bourgeoissii bourgeoissii* (C. Powell, personal commun., 2001). A devitrified tuff bed is 10.5 m below the conglomerate bed where the count took place. The sandstone throughout this section is quartz rich. A brown sandstone similar to the lower beds of LMH 10 is located 38.5 m below the conglomerate bed. A second conglomerate bed 52.5 m below the counted bed has a composition that appears to be similar to that of LMH 11 and is contained in a sandstone that is bluish in color and appears to be andesitic in composition.

The conglomerate where the count took place is composed of 3 beds; all 3 beds contain shell fragments, the percentage of which increases up section. The average clast size in the 3 beds decreases up section. All three units are clast supported. The beds are partially separated by laminated sandstone, giving the impression of partially amalgamated beds. The lower conglomerate bed is approximately 30 cm thick and contains 2- to 3-cm pectens. The middle bed is also about 30 cm thick and appears to have been scoured and filled. The shells in this bed are large (5-8 cm) pectens. The top of the uppermost conglomerate bed is not exposed. The fossil population in the uppermost bed is more heterogeneous than that in the lower two beds and contains *Striostrea? bourgeoissii bourgeoissii* and several pectens like those found in the lower bed.

The fossils indicate that the environment of deposition for this location is coastal marine. The bedding style suggests lower shore face or maybe upper shore face. If the lower conglomerate in this section corresponds to the bed at LMH 10, then the unit has a lateral transition from fluvial to marine in less than 400 m.

Shell Ridge 1

This sample locality is at the base of the Miocene section in the Cierbo "sandstone and conglomerate" located east of Shell Ridge. The section is composed primarily of fine- to medium-grained sandstone with a basal conglomerate. The sandstone beds near the conglomerate are from 1 to 30 cm thick. The section also contains trough cross-beds approximately 10 cm thick. Some beds contain possible dish structures, some of which are quite large (20 cm). Other beds contain burrows 2.5 cm in diameter showing no preferred orientation. The sandstone containing the sampled conglomerate is poorly to moderately sorted with stringers of granules and pebbles. The stringers form amalgamated, stacked beds with broad gentle scours.

Based on the presence of trough cross-beds, dish structures, and trace fossils, the environment of deposition at this location appears to be upper shore face.

Approximately 100 m up section from SR1 near the top of the Cierbo "sandstone and conglomerate" is a shell hash. This bed is either continuous for more than 1 km or occupies a horizon with several other shell hashes. The upper shell hash shows a highly diversified fauna that includes ornate (crenellate) bivalves, at least two species of gastropods (Naticidae?), and a high-spired gastropod. The assemblage in this bed appears to be distinct from that of the overlying beds in the Cierbo and Neroly sandstones. At approximately the same stratigraphic interval as the uppermost shell hash in the Cierbo "sandstone and conglomerate" is a horizon of carbonate nodules.

Shell Ridge 2

This location is in Neroly Sandstone to the west of Shell Ridge, where the Neroly forms a set of low ridges running parallel to Shell Ridge. The section is composed of 1- to 2-m-thick, fossiliferous conglomerate beds. The surrounding sandstone is massive or cross-laminated. The conglomerate is matrix supported. The sand-size matrix, as well as the surrounding sandstone, is well sorted. All the conglomerate clasts at this location are well rounded. The shell material is mostly composed of heavy-shelled bivalve fragments showing a crude alignment parallel to the bedding plane.

The probable environment of deposition is shallow marine, most likely upper shore face. The conglomerate probably is a storm-generated deposit, maybe foreshore. However, the large number of high-energy deposits recorded suggest the possibility that these beds were laid down by high-energy currents, possibly part of an inner delta bar complex.

Shell Ridge 3

SR 3 has been offset by faulting, so that it lies to the west of Shell Ridge but it is stratigraphically equivalent to the shell hashes that hold up Shell Ridge. The conglomerate bed at SR 3 is approximately 1 to 2 m thick.

At this locality, mosses obscure much of the outcrop. The conglomerate bed appears to be massive, as do the limited outcrops of the encasing sandstone. The conglomerate appears to be clast supported, and it contains abundant fossils. Most of the fossils present are casts of clam valves that in some places are intercalated, suggesting winnowing by strong currents. Fragments of large oysters are also present but less abundant than the clams.

The environment of deposition for the conglomerate based on the faunal assemblage is marginal marine or estuarine. The large number of intercalated clam valves suggest that the environment of deposition was shore face.

Shell Ridge 4

This location is in the Neroly Sandstone. The lower half of the unit is composed of large-scale cross-bedded sandstone, similar to that found at Los Medanos Hills 6. At the stratigraphic level where the count took place the Neroly is composed of tabular-bedded sandstone. The outcrop color is light brownish gray on weathered surfaces and medium-gray on fresh surfaces. Many tabular beds contain shell hashes dominated by bivalves and some *Astrodapsis* sp., gastropods, and *Striostrea*? *bourgeoissii bourgeoissii*.

Intercalated with these beds are lenses of matrix-supported conglomerate and sandstone. Individual beds in the conglomerate lenses show reverse and reverse-to-normal grading, with some mud rip-up clasts near the base of each bed. Normally graded beds are only rarely present. Individual beds are commonly intercalated with mudstone beds 10 to 20 cm thick, of the same color and texture as the mud rip-up clasts. Amalgamation of the conglomerate beds is commonly visible because of the incomplete scouring of the mudstone beds. The conglomerate beds show a strong bimodality in sorting; sand-size fractions are uniformly medium grained and all coarse clasts are in the –2 to –3 phi size range. The sand-size fraction in the conglomerate beds is the same blue color as the underlying fluvial sandstone. All the conglomerates are matrix supported. The mudstone beds commonly contain terrigenous plant material, in contrast to the enclosing sandstone beds, which commonly contain marine invertebrate fossils.

The environment of deposition for the upper half of the section, based on the fossil assemblage, appears to be estuarine. The sorting and bedding architecture in the lens where the conglomerate count took place suggest that the lens is probably a subaqueous debris flow; the upper portions may be turbidites.

Shell Ridge 5

Located at the same stratigraphic level in the Cierbo "sandstone and conglomerate" as Shell Ridge 1, this location is next to a small, unmapped fault, and many of the clasts in the conglomerate have been fractured. The encompassing poorly sorted, micaceous sandstone is not well exposed. Fossilized wood was noted in the float at this location. The conglomerate bed here is matrix supported. It was not possible to discern any clast imbrication in the beds. All the clasts are well rounded, but the sphericity of the clasts is highly variable, suggesting that some may have been recycled.

Because the conglomerate lacks any fossils and the encasing sandstone is poorly exposed, the environment of deposition is not easy to determine for this location. Nearby outcrops contain marine bivalves suggesting either upper- or lower-shore face for the surrounding section; however, a fluvial environment of deposition for the conglomerate bed can not be ruled out.

Shell Ridge 6

Located near the Neroly-Cierbo contact, SR 6 is in a debris-flow scar approximately 35 m below the top of the Cierbo. Multiple conglomerate lenses are present at this site and the counting was done in several of them. Bedding in the surrounding sandstone and within the conglomerate lenses is massive. The conglomerate is matrix supported and contains fossils. The fossil population includes bivalves and *Astrodapsis* sp. Many of the clam valves are up to 5 mm thick, although others are much more delicate.

The environment of deposition is marine. This interpretation is primarily based on the fossil population, which is indicative of a coastal marine setting.

Altamont Hills 1

The count location is in a conglomerate in the Neroly Sandstone. The enclosing sandstone contains very large (10 m?) low-angle cross-beds and abundant soft-sediment deformation structures. The sandstone is medium grained and moderately to well sorted. No fossils were noted in the section. The conglomerate bed has meter-scale cross-beds. It is clast supported with almost no matrix material. Clasts are well sorted and there appears to be a general orientation to the clasts at this location so only loose clasts were counted and their actual medial axis was directly measured.

The pervasiveness of the cross-bedding and the clast-supported framework, along with the soft-sediment deformation features, suggest a fluvial environment but a lacustrine delta can not be entirely ruled out.

Altamont Hills 2

The second Altamont Hills location is less than 2 km to the northwest of AH 1, and the section is the same as that at Altamont Hills 1. Like AH 1, the environment of deposition at AH 2 is inferred to be fluvial.

Happy Valley 1

This sample location is in the Neroly Formation. The composition of the sandstone is andesitic, and most of the rock is the typical Neroly bluish-gray color. Some sections are a buff color but there appears to be no stratigraphic correlation to the color changes. The color change here seems to be controlled by cementation; the bluish-gray sandstone is carbonate cemented. The carbonate-cemented beds are fossiliferous, and the fossils include gastropods, bivalves, and plant material, probably reeds.

The conglomerate bed and the section immediately surrounding it contain heavy-shelled bivalves. The conglomerate bed is divided into a lower, parallel-bedded section and an upper, trough-cross-bedded section by an inversely graded sandstone bed 40 cm thick. The lower conglomerate has parallel bedding 20 to 50 cm thick, is matrix supported, and poorly to very poorly sorted. The upper conglomerate has meter-scale trough cross-beds and is clast supported and composed of angular to very angular clasts.

Based primarily on the fossils, the environment of deposition was marginal marine. The large average clast size and cross-bedding suggest a high-energy environment, probably coastal marine.

APPENDIX B DESCRIPTION OF VOLCANIC CLASTS

Thesis Location	Lith. Type	# of clasts	% of clasts	Color	Phenocrysts
LMH 1					
	Rhyolite	6	2	Weathered 5Y 7/2 Fresh 10Y 6/2	Plagioclase Hornblende
	Rhyolite	10	4	Weathered 5Y 6/4 Fresh 5GY 6/1	Plagioclase
	Rhyolite	7	3		
	Rhyolite	1	0		Quartz
Rhyolite		**24**	**9**		
	Andesite	30	11	10YR 8/2	Hornblende Plagioclase
	Andesite	19	7	Weathered 5Y 7/2 Fresh N5	Hornblende Plagioclase
	Andesite	40	15	5Y 7/2	Hornblende Plagioclase
	Andesite	43	16	5Y 6/1	Feldspar
	Andesite	15	6	5GY 6/1 Fresh	Plagioclase Quartz Hornblende
	Andesite	27	10	5GY 6/1	Aphanitic Aphanitic
	Andesite	16	6	Fresh 5Y 6/1 Weathered 5YR 7/2	Feldspar Mafics (undetermined)
	Andesite	26	10	Fresh 10G 6/2 Weathered 5Y 7/2	Pyroxene Feldspar
	Andesite	8	3		Hornblende Plagioclase
Andesite		**224**	**85**		
	Basalt	16	6		Aphanitic
Basalt		**16**	**6**		
No Data		**0**	**0**		
total		**289**			
LMH 4					
	Rhyolite	3	4	5Y 6/1	Plagioclase
Rhyolite		**3**	**4**		
	Andesite	41	49	10R 5/4	Plagioclase Hornblende Pyroxene
	Andesite	7	8	5Y 6/1	Hornblende Feldspar
	Andesite	5	6	5G 5/2	Plagioclase
	Andesite	2	2	5YR 2/2	Plagioclase Mafics (undetermined)
	Andesite	2	2	10YR 6/2	Plagioclase Pyroxene Hornblende
	Andesite	4	5	Weathered 5Y 8/1 Fresh N4	Plagioclase Mafics (undetermined)
Andesite		**61**	**73**		
	Basalt	2	2	Weathered 5Y 7/1 Fresh N3	Aphanitic
	Basalt	10	12	Weathered 5B 7/1 Fresh N4	Aphanitic
	Basalt	8	10	Weathered 10Y 6/2 Fresh N3	Aphanitic
Basalt		**94**	**112**		
No Data		**0**	**0**		
total		**142**			
LMH 5					
	Rhyolite	13	7	5Y 6/1	Quartz Mafics (undetermined)
	Rhyolite	14	7	10YR 8/2	Aphanitic
	Rhyolite	3	2	Weathered 5Y 5/2 Fresh 5YR 8/1	Aphanitic
	Rhyolite	2	1	10YR 5/4	e Biotite
	Rhyolite	10	5	5Y 5/2	Plagioclase
Rhyolite		**42**	**21**		
	Andesite	11	6	Weathered 10YR 6/2 Fresh N4	Plagioclase Hornblende
	Andesite	1	1	10R 4/2	K-spar Mafics (undetermined)
	Andesite	10	5	5G 6/1	Plagioclase Quartz Hornblende Pyroxene
	Andesite	21	11	5G 4/1	Plagioclase
	Andesite	3	2	5Y 4/1	Hornblende Pyroxene Plagioclase
	Andesite	3	2	5G 4/1	Plagioclase Hornblende
Andesite		**49**	**25**		
	Basalt	22	11	Weathered 10YR 6/2 Fresh N3	Pyroxene Hornblende Plagioclase
	Basalt	6	3	Weathered 10G 6/2, 5Y 6/1 Fresh N3	Aphanitic
	Basalt	18	9	N 3	Aphanitic
	Basalt	58	29	, ,	
	Basalt	2	1	5YR 3/2	Aphanitic
	Basalt	2	1	5GY 2/1	Aphanitic
Basalt		**108**	**54**		
	No Data	1	1		
No Data		**1**	**1**		
total		**315**			
LMH 6					
	Rhyolite	10	3	5R 4/2	Quartz Biotite Plagioclase
	Rhyolite	21	7	5y 4/1	Quartz Biotite
	Rhyolite	38	13	10y r 6/2	Quartz Biotite Plagioclase
Rhyolite		**69**	**23**		
	Andesite	10	3	5YR 4/1	Pyroxene Plagioclase
	Andesite	45	15	5R 4/2	Plagioclase Mafics (undetermined)
	Andesite	1	0	10 R 5/4	Hornblende Plagioclase K-spar Pyroxene
	Andesite	64	21	5YR 7/2	Hornblende Plagioclase K-spar
	Andesite	25	8	5R 6/2	Hornblende Pyroxene Plagioclase
	Andesite	21	7	5YR 4/1	Plagioclase Hornblende
Andesite		**166**	**55**		
	Basalt	5	2		
	Basalt	23	8	N4	Pyroxene
	Basalt	38	13	N 3	Aphanitic
Basalt		**66**	**22**		
No Data		**0**	**0**		
total		**475**			

APPENDIX B DESCRIPTION OF VOLCANIC CLASTS

Thesis Location	Lith. Type	# of clasts		% of clasts		Color	Phenocrysts
LMH 7							
	Rhyolite	34		43		5Y 6/4	Quartz Plagioclase Biotite
	Rhyolite	11		14		10YR 6/2	Quartz Plagioclase
	Rhyolite	18		23		5Y 7/2	Plagioclase
Rhyolite			63		79		
	Andesite	7		9		N 5	Plagioclase K-spar Hornblende
	Andesite	2		3		5RP 2/2	Plagioclase K-spar
Andesite			9		11		
	Basalt	8		10		N4	Plagioclase Mafics (undetermined)
Basalt			8		10		
No Data			0		0		
total			118				
LMH 10							
	Rhyolite	8		15		5Y 5/2	Plagioclase
	Rhyolite	1		2		5Y 7/2	K-spar Mafics (undetermined)
Rhyolite			9		16		
	Andesite	7		13		5Y 7/2	Plagioclase Pyroxene
	Andesite	6		11		5Y 6/1	Hornblende Plagioclase
	Andesite	11		20		Weathered 5Y 7/2 Fresh N7	Plagioclase Mafics (undetermined)
	Andesite	13		24		10Y 6/2	Plagioclase Hornblende
	Andesite	8		15			
Andesite			45		82		
	Basalt	1		2		N1	Aphanitic
Basalt			1		2		
No Data			0		0		
total			91				
LMH 11							
	Rhyolite	5		10		Weathered 5Y 6/1 Fresh N7	Plagioclase Quartz Biotite
Rhyolite			5		10		
	Andesite	5		10		Weathered 10YR 6/2 Fresh N7	Hornblende Plagioclase
	Andesite	10		20		5Y 7/2	Hornblende Plagioclase Quartz
	Andesite	1		2		Weathered 10YR 6/2 Fresh 10YR 4/2	Hornblende
	Andesite	10		20		Weathered 10Y 6/2 Fresh N5	Hornblende
Andesite			67		131		
	Basalt	4		8		N5	Aphanitic
	Basalt	16		31		Weathered 5Y 8/1 Fresh N3	Plagioclase Hornblende
Basalt			20		39		
No Data			0		0		
total			31				
SR 1							
	Rhyolite	3		43		Fresh N7	Hornblende Plagioclase Quartz Biotite
	Rhyolite	2		29		5Y 8/1	Plagioclase Hornblende Biotite
Rhyolite			5		71		
	Andesite	1		14		5GY 4/1	Plagioclase Hornblende
	Andesite	1		14		Weathered N4 Fresh N7	Plagioclase K-spar Mafics (undetermined)
Andesite			2		29		
Basalt			0		0		
No Data			0		0		
total			11				
SR 2							
Rhyolite			0		0		
	Andesite	188		75		N5	Pyroxene Hornblende Plagioclase
	Andesite	64		25		5R 5/4	Pyroxene Plagioclase Hornblende
Andesite			252		100		
Basalt			0		0		
No Data			0		0		
total			252				
SR 3							
	Rhyolite	1		5			
	Rhyolite	1		5		Weathered 10YR 6/2 Fresh 5B 6/2	Plagioclase Quartz Mafics (undetermined)
	Rhyolite	1		5		Weathered 10R 6/2 Fresh N7	Plagioclase Quartz Mafics (undetermined)
Rhyolite			3		15		
	Andesite	5		25		Weathered 5Y 4/4 Fresh 10Y 6/2	Feldspar Hornblende
	Andesite	3		15			
	Andesite	2		10		5GY 4/1	Plagioclase
Andesite			10		50		
	Basalt	2		10		5YR 4/1	Plagioclase Hornblende
	Basalt	5		25		Weathered 10YR 6/2 Fresh N5	Plagioclase Hornblende K-spar
Basalt			7		35		
No Data			0		0		
total			27				

APPENDIX B DESCRIPTION OF VOLCANIC CLASTS

Thesis Location	Lith. Type	# of clasts		% of clasts		Color	Phenocrysts
SR 4							
Rhyolite			**0**		**0**		
	Andesite	36		9		N6	Hornblende Pyroxene
	Andesite	135		35		N6	Aphanitic
	Andesite	130		33		N5	Hornblende Pyroxene
	Andesite	71		18		5Y 5/4	Pyroxene
	Andesite	17		4		5Y 5/4	Plagioclase
Andesite			**389**		**100**		
Basalt			**0**		**0**		
No Data			**0**		**0**		
total			**389**				
SR 5							
	Rhyolite	13		22		5YR 8/1	Hornblende Pyroxene Plagioclase
	Rhyolite	4		7		10YR 8/2	Plagioclase Hornblende
	Rhyolite	1		2		Weathered 5YR 5/2 Fresh N7	Pyroxene Plagioclase
Rhyolite			**18**		**30**		
	Andesite	3		5		5YR 7/2	Plagioclase Quartz Pyroxene
	Andesite	16		27		5Y 6/1	Plagioclase K-spar Hornblende
	Andesite	4		7		10YR 8/2	Pyroxene
	Andesite	1		2		Weathered 10YR 6/2 Fresh N4	Plagioclase Pyroxene
	Andesite	1		2		5YR 4/1	Plagioclase K-spar
	Andesite	3		5		5Y 6/1	Aphanitic
	Andesite	3		5		5YR 3/4	Aphanitic
	Andesite	1		2		Weathered 5YR 7/2 Fresh N3	Aphanitic
Andesite			**32**		**53**		
	Basalt	10			17	Weathered 10YR 6/2 Fresh 5Y 4/1	Plagioclase
Basalt			**10**		**17**		
No Data			**0**		**0**		
total			**32**				
SR 6							
Rhyolite			**0**		**0**		
	Andesite	4		21			
	Andesite	4		21			
	Andesite	3		16			
	Andesite	3		16			
	Andesite	2		11			
	Andesite	2		11			
	Andesite	1		5			
Andesite			**19**		**100**		
Basalt			**0**		**0**		
No Data			**0**		**0**		
total			**19**				
SR 6-2							
Rhyolite			**0**		**0**		
	Andesite	100		39		5 YR 4/2	Plagioclase Mafics (undetermined)
	Andesite	3		1		10R 4/2	Plagioclase Pyroxene Mafics (undetermined)
	Andesite	45		18		5R 4/6	Plagioclase Hornblende
	Andesite	1		0		5Y 4/1	Plagioclase Hornblende
	Andesite	3		1		5GY 2/1	Plagioclase Hornblende
	Andesite	4		2		5GY 4/1	Hornblende Plagioclase
	Andesite	29		11		10 Y 4/2	Plagioclase Hornblende
	Andesite	5		2		5Y 7/2	Plagioclase Hornblende Pyroxene
	Andesite	30		12		N4	Plagioclase Mafics (undetermined)
	Andesite	28		11		5Y 5/2	Plagioclase Hornblende Pyroxene
	Andesite	4		2		5Y 4/1	Plagioclase Pyroxene
	Andesite	1		0		10R 4/2	Mafics (undetermined)
	Andesite	2		1		10YR 6/2	Hornblende Plagioclase
Andesite			**255**		**99**		
Basalt			**2**		**1**		
	Basalt	2		1		10YR 6/2	Pyroxene Plagioclase Mafics (undetermined)
No Data			**0**		**0**		
total			**255**				
AH 1 AND 2							
Rhyolite		**0**			**0**		
	Andesite	74		10		Weathered 5YR 6/2 Fresh N4	Pyroxene Hornblende K-spar
	Andesite	281		39		Weathered 5Y 6/1 Fresh 5Y 4/1	Plagioclase Hornblende
	Andesite	128		18		5GY 4/1	Plagioclase Hornblende Pyroxene
	Andesite	36		5		5YR 5/2	Plagioclase Hornblende Pyroxene
	Andesite	12		2		5Y 6/1	Plagioclase Hornblende
	Andesite	46		6		N6	Plagioclase Hornblende
	Andesite	63		9		5Y 6/1	Plagioclase Hornblende
	Andesite	15		2		5R 5/4	Plagioclase Hornblende Pyroxene
	Andesite	10		1		5Y 6/2	Plagioclase Hornblende Pyroxene
	Andesite	20		3		5Y 4/1	Plagioclase Pyroxene
	Andesite	11		2		Weathered 10R 4/2 Fresh 5YR 6/1	Plagioclase Hornblende Pyroxene K-spar
	Andesite	7		1		5GY 2/1	Plagioclase
Andesite		**703**			**98**		
Basalt		**0**			**0**		
	No Data	11		2			
No Data		11			2		
total		703					